VISIT…

ROTATIONAL MOLDING TECHNOLOGY

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WILLIAM ANDREW PUBLISHING
Norwich, New York

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Library of Congress Catalog Card Number: 2001037322
ISBN 1-884207-85-5
Printed in the United States of America

Published in the United States of America by
Plastics Design Library / William Andrew Publishing
13 Eaton Avenue
Norwich, New York 13815
1-800-932-7045
www.williamandrew.com

10 9 8 7 6 5 4 3 2 1

Library of Congress Cataloging-in-Publication Data

Crawford, R. J.
Rotational molding technology / R.J. Crawford, J.L. Throne.
p.cm.
Includes bibliographical references and index.
ISBN 1-884207-85-5 (alk. paper)
1. Rotational molding. I. Throne, James L., 1937- II. Title.

TP1150 .C76 2001
668.4′12–dc21

2001037322

Preface

Rotational molding is the process of producing hollow parts by adding plastic powder to a shell-like mold and rotating the mold about two axes while heating it and the powder. During rotation, the powder fuses against the inner mold surface into a bubble-free liquid layer. The polymer is then cooled to near room temperature, and the resulting hollow part is removed. The cyclical process is then repeated. Although the rotational molding concept is more than 150 years old, the production of hollow plastic parts for such varied applications as outdoor playground equipment, liquid storage tanks, furniture, and transportation products is around 50 years old. With the advent of process controls and improved polymers, the U.S. market in the year 2000 has exceeded one billion pounds or 450,000 kg. Worldwide production is estimated at more than twice the U.S. market. During most of the 1990s, the rotational molding industry was growing at 10% to 15% per year.

With the growth of rotational molding has come an increasing interest in the complex technical aspects of the process. As detailed in this monograph, the heating process involves the slow rotation of relatively fine particulate powders in a metal mold, the heating of these powders until they begin to fuse and adhere to the metal mold, the coalescence of the powder through building of powder-to-powder bridges, the melting of the powder particles into a densified liquid state, and finally, the dissolution of air bubbles. The cooling process involves temperature inversion in the liquid layer against the mold surface, cooling and crystallization of the polymer into a solid, and controlled release of the polymer from the mold surface to minimize part warpage and distortion. Ancillary aspects of the rotational molding process, including grinding, mold making and mold surface preparation, and part finishing are also included. Characteristics of rotationally molded polymers, including standard tests such as melt index and cross-link density are detailed. Liquid rotational molding, the oldest form of rotational molding, is also discussed.

The objective of this monograph is to clarify and quantify some of the technical interactions in the process. The monograph relies heavily on technologies in other disciplines, such as powder mechanics, heat transfer, and soil mechanics. Although it follows other treatises in rotational molding, most notably:

Glenn L. Beall, *Rotational Molding: Design, Materials, Tooling and Processing*, Hanser Publishers, Munich, 1998.

R.J. Crawford, Editor, *Rotational Moulding of Plastics*, 2nd ed., Research Studies Press, Taunton, Somerset England, 1996.

P.F. Bruins, Editor, *Basic Principles of Rotational Molding*, Gordon and Breach, New York, 1971.

it distinguishes itself from them by approaching the technical aspects of the subject in a single voice. It was not our objective to repeat material found in other treatises but, instead, to extend the technological aspects of the industry. The authors refer the reader to the appropriate literature for further reading, wherever possible. It is the authors' hope that this monograph is a seamless story of the advanced aspects of the rotational molding process.

The monograph consists of seven chapters:

Chapter 1. *Introduction to Rotational Molding*. Brief descriptions of the general characteristics of the process and some historical aspects are followed by a synopsis of typical rotationally molded parts and a comparison of the process with other ways of making hollow parts, such as industrial blow molding and twin-sheet thermoforming. A brief description of the importance of measurement in rotational molding follows.

Chapter 2. *Rotational Molding Polymers*. Polyolefin is the major rotationally molded polymer class, with polyethylenes representing more than 80% of all polymers rotationally molded. Brief descriptions of the characteristics of the polymers in this class are followed by descriptions of vinyls, nylons, and liquid polymers such as PVC plastisols, silicones, and thermosetting polymers.

Chapter 3. *Grinding and Coloring.* Rotational molding uses solid polymer powders with particle sizes ranging from -35 mesh or 500 microns to +200 mesh or 60 microns. Powders are usually prepared from suppliers' pellets by grinding. This chapter focuses on particle size, particle size distribution, particle size analysis techniques, and optimum particle shape. In addition, pigments and property enhancers are reviewed in detail.

Chapter 4. *Rotational Molding Machines*. A brief overview is given of the myriad types of commercial rotational molding machines, including rock-and-roll machines, shuttle machines, clamshell machines, fixed turret machines, and independent-arm machines. The importance of oven and cooling chamber design is discussed, as is energy conservation and efficiency.

Chapter 5. *Mold Design*. Mold materials, such as steel, aluminum, and electroformed nickel are compared in terms of their characteristic strengths and thermal efficiencies. Various mold design aspects are discussed technically, and the various types of mold releases are reviewed.

Chapter 6. *Processing*. Powder flow behavior in the rotating mold, particle-to-particle adhesion, and densification are considered technically. The mechanism of bubble removal is discussed and the rationale for oven cycle time is reviewed. Thermal profile inversion and recrystallization effects during cooling are considered, as are warpage and shrinkage, and the effect of pressurization. The mechanism of foaming and the unique characteristics of foam generation in a low-pressure process completes the chapter.

Chapter 7. *Mechanical Part Design*. The chapter provides an overview of those technical aspects of the process that influence part design, including powder flow into and out of acute angles, and the effect of processing on properties and polymer characteristics. Other aspects of part design, such as surface quality, mechanical characteristics, and design properties of foams are included.

The monograph also includes a brief troubleshooting guide that relates processing problems to technical aspects of the process, and a units conversion table.

In 1976, several rotational molding companies formed The Association of Rotational Molders, with the stated objective of advancing the general knowledge in this processing field. During this past quarter-century, ARM has provided its members with business and technical guidelines through conferences and exhibitions. In 2000, The Society of Plastics Engineers chartered the Rotational Molding Division to provide a forum for individuals interested in the technical aspects of the industry. The authors of this monograph have been actively involved in the promotion of technology in both these organizations. It is our belief that this monograph can act as a basis for the further technical development of this rapidly growing industry.

September 2000

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Roy J. Crawford, FREng, B.Sc, Ph.D., D.Sc., FIMech E., FIM. Professor Roy Crawford obtained a first-class honours degree in Mechanical Engineering from the Queen's University of Belfast, Northern Ireland, in 1970. He went on to obtain Ph.D. and D.Sc. degrees for research work on plastics. Over the past 30 years he has concentrated on investigations of the processing behavior and mechanical properties of plastics. He has published over 200 papers in learned journals and conferences during this time. He has also been invited to give keynote addresses at conferences all over the world. He is the author of five textbooks on plastics and engineering materials.

Dr. Crawford is currently Pro Vice Chancellor for Research and Development at the Queen's University of Belfast. Previously he held the posts of Professor of Mechanical Engineering at the University of Auckland, New Zealand, and Professor of Engineering Materials and Director of the School of Mechanical and Process Engineering at the Queen's University of Belfast. He was also Director of the Polymer Processing Research Centre and the Rotational Moulding Research Centre at Queen's University. He has carried out research work on most plastics processing methods. Of particular importance is the work done on rotational molding, which has resulted in a number of patented techniques for recording temperatures during the process and improving the quality of molded parts.

Professor Crawford is a Fellow of the Institution of Mechanical Engineers and a Fellow of the Institute of Materials. In 1997, he was elected Fellow of the Royal Academy of Engineering. He has been awarded a number of prizes for the high quality of his research work, including the prestigious Netlon Medal from the Institute of Materials for innovative contributions to the molding of plastics.

James L. Throne. Jim Throne is President of Sherwood Technologies, Inc., a polymer processing consulting firm he started in 1985. STi specializes in advanced powder processing, thermoforming, and thermoplastic foams. Jim has more than twenty years industrial experience in plastics and taught ten years in universities. In 1968 at American Standard he led a technical team that successfully rotationally molded toilet seats from ABS using electroformed nickel molds. Throne has degrees in Chemical Engineering from Case Institute of Technology and University of Delaware. He is a Fellow of the Institute of Materials and of the Society of Plastics Engineers. He has published nearly two hundred technical papers and has nine patents. This is his eighth book on polymer processing.

Contents

Preface v

About the Authors ix

1. Introduction to Rotational Molding **1**

1.0 Introduction 1
1.1 The Process 2
1.2 The Early Days 4
1.3 Materials 6
1.4 Advantages and Disadvantages 9
1.5 General Relationships between Processing Conditions and Properties 11
References 14

2. Rotational Molding Polymers **19**

2.0 Introduction 19
2.1 General Characteristics of Polymers 19
2.2 Polymers as Powders and Liquids 21
2.3 Polyethylene Types 22
2.3.1 Low-Density Polyethylene 22
2.3.2 Medium-Density Polyethylene 23
2.3.3 High-Density Polyethylene 24
2.3.4 Linear Low-Density Polyethylene 25
2.3.5 Ethylene Vinyl Acetate 27

This page has been reformatted by Knovel to provide easier navigation.

2.4 Polypropylene 28
2.5 PVC – Plastisols, Drysols, and Powdered Flexible Compounds 30
2.6 Nylons 31
2.7 Other Polymers 33
2.7.1 Polycarbonate 33
2.7.2 Cellulosics 34
2.7.3 Acrylics 35
2.7.4 Styrenics 35
2.8 Liquid Polymers 36
2.8.1 PVC Plastisols 38
2.8.2 Polycaprolactam 39
2.8.3 Polyurethane 41
2.8.4 Unsaturated Polyester Resin 42
2.8.5 Silicones 43
2.9 In-Coming Material Evaluation 43
2.9.1 Melt Index and Melt Flow Index 44
2.9.2 Sieving 46
2.10 Product Testing Protocols and Relationship to Polymer Characteristics 47
2.10.1 Actual Part Testing – Protocol 47
2.10.2 Actual Part Testing – Entire Parts 49
2.10.3 Actual Part Testing – Sections 50
2.10.3.1 Molded Part Density 51
2.10.3.2 Drop Tests 51
2.10.3.3 ASTM Tests for Mechanical Properties 54
2.10.3.4 Color 55
2.10.3.5 Chemical Tests 56
2.10.3.6 Environmental Stress Crack Test 57

This page has been reformatted by Knovel to provide easier navigation.

2.10.3.7 Chemical Crosslinking and the Refluxing Hexane Test 58
2.10.3.8 Weathering 61
2.10.3.9 Odor in Plastics 62
2.10.3.10 Fire Retardancy 62
2.11 Desirable Characteristics of a Rotational Molding Resin 64
References 65

3. Grinding and Coloring 69

3.0 Introduction 69
3.1 General Issues Relating to Grinding 73
3.2 Particle Size Distribution 75
3.2.1 Particle Size Analysis 77
3.2.1.1 Dry Sieves 77
3.2.1.2 Elutriation 78
3.2.1.3 Streaming 78
3.2.1.4 Sedimentation 78
3.2.1.5 Fluidization 79
3.2.2 Presentation of PSD Data 79
3.3 Particle Shape 81
3.4 Dry Flow 83
3.5 Bulk Density 84
3.5.1 Packing of Particles 85
3.6 Factors Affecting Powder Quality 88
3.6.1 Gap Size 89
3.6.2 Number of Mill Teeth 90
3.6.3 Grinding Temperature 90
3.7 Grinding Costs 91
3.8 Micropelletizing 93

This page has been reformatted by Knovel to provide easier navigation.

3.9 Polyvinyl Chloride 96
3.10 Coloring of Plastics for Rotational Molding 96
3.10.1 Dry Blending 97
3.10.2 High Speed Mixing (Turbo Blending) 99
3.10.3 Compounding 101
3.10.4 Types of Pigments 101
3.10.5 Aesthetics of Rotationally Molded Parts 104
3.10.6 Other Types of Additives 105
References 108

4. Rotational Molding Machines 111

4.0 Introduction 111
4.1 Types of Rotational Molding Machines 112
4.1.1 Rock-and-Roll Machines 113
4.1.2 Clamshell Machines 115
4.1.3 Vertical Machines 116
4.1.4 Shuttle Machines 116
4.1.5 Fixed-Arm Carousel Machine 117
4.1.6 Independent-Arm Machine 118
4.1.7 Oil Jacketed Machines 119
4.1.8 Electrically Heated Machines 120
4.1.9 Other Types of Machines 121
4.2 Machine Design Considerations 122
4.2.1 Mold Swing 122
4.2.2 Mold Speed 125
4.2.3 Speed Ratio 126
4.3 The Oven 127
4.3.1 Oven Design 129
4.3.2 Heat Transfer in Oven 131
4.3.3 Oven Air Flow Amplification 135

This page has been reformatted by Knovel to provide easier navigation.

4.4 Cooling 137
4.5 Process Monitors 138
4.5.1 Internal Air Temperature Measurement in Rotational Molding 140
4.5.2 Infrared Temperature Sensors 144
4.6 Servicing 144
4.7 Advanced Machine Design 145
References 147

5. Mold Design 149

5.0 Introduction 149
5.1 Mold Materials 151
5.1.1 Sheet Steel 151
5.1.2 Aluminum 152
5.1.3 Electroformed Nickel 154
5.2 Mechanical and Thermal Characteristics of Mold Materials 156
5.2.1 Equivalent Mechanical Thickness 156
5.2.2 Equivalent Static Thermal Thickness 157
5.2.3 Equivalent Transient Thermal Thickness 159
5.3 Mold Design 160
5.3.1 Parting Line Design 161
5.3.1.1 Butt or Flat 161
5.3.1.2 Lap Joint 162
5.3.1.3 Tongue-and-Groove 162
5.3.1.4 Gaskets 163
5.3.2 Mold Frame 165
5.3.3 Clamping 166
5.3.4 Pry Points 167

This page has been reformatted by Knovel to provide easier navigation.

5.3.5 Inserts and Other Mechanical Fastening Methods 168
5.3.5.1 Self-tapping Screws 168
5.3.5.2 Mechanical Fastening 169
5.3.5.3 Postmolded Insert 169
5.3.5.4 Molded-in Insert 169
5.3.6 Threads 171
5.3.7 Cut-out Areas 172
5.3.8 Kiss-offs 172
5.3.9 Molded-in Handles 173
5.3.10 Temporary Inserts 173
5.4 Calculation of Charge Weight 174
5.4.1 Methodology 174
5.4.2 Maximum Part Wall Thickness for a Given Mold 180
5.5 Venting 183
5.5.1 Simple Estimate for Vent Size 186
5.5.2 Types of Vent 193
5.5.3 Is a Vent Necessary? 195
5.6 Mold Surface Finish 196
5.7 Mold Releases 196
5.7.1 Spray-on Zinc Stearates 197
5.7.2 Silicones 197
5.7.3 Disiloxanes 197
5.7.4 Fluoropolymers 197
5.7.5 Mold Surfaces to be Coated 198
5.7.6 Controlled Release 199
5.7.7 Mold Release Cost 199
References 200

This page has been reformatted by Knovel to provide easier navigation.

6. Processing 201

6.0 Introduction to Heating 201
6.1 General Anatomy of the Rotational Molding Cycle 201
6.2 General Process Description 204
6.3 Powder Behavior 205
6.4 Characteristics of Powder Flow 207
6.5 Rheology of Powder Flow 210
6.6 Heat Transfer Concepts Applied to Rotational Molding 213
6.7 Heating the Mold 213
6.8 Heating Powder 215
6.8.1 Transient Heating of an Individual Particle 215
6.8.2 Heating the Powder Bed 217
6.9 Tack Temperature 219
6.10 Mold Cavity Air Heating Prior to Powder Adhesion to Mold Surface 221
6.11 Bed Depletion 222
6.12 Particle Coalescence 223
6.13 Densification 234
6.14 Phase Change During Heating 243
6.15 The Role of Pressure and Vacuum 244
6.16 Mathematical Modeling of the Heating Process 245
6.17 Total Oven Cycle Time 251
6.18 Cooling and the Optimum Time for Removal from Oven 259
6.19 Some Comments on Heat Transfer During Cooling 259
6.20 Thermal Profile Inversion 262
6.21 Cooling and Recrystallization 266
6.22 Air Cooling – Heat Removal Rate 274
6.23 Water Cooling – Heat Removal Rate 275

This page has been reformatted by Knovel to provide easier navigation.

6.24 Pressurization 276
6.25 Part Removal 276
6.26 Effect of Wall Thickness on Cooling Cycle Time 277
6.27 Overview and Summary of Thermal Aspects of the Rotational Molding Process 278
6.28 Introduction to Liquid Rotational Molding 278
6.29 Liquid Polymers 278
6.30 Liquid Rotational Molding Process 279
6.30.1 Liquid Circulating Pool 280
6.30.2 Cascading Flow 281
6.30.3 Rimming Flow 281
6.30.4 Solid Body Rotation 281
6.30.5 Hydrocyst Formation 282
6.30.6 Bubble Entrainment 284
6.30.7 Localized Pooling 285
6.31 Process Controls for Liquid Rotational Molding 285
6.32 Foam Processing 287
6.32.1 Chemical Blowing Agent Technology 288
6.32.2 Single Layer vs. Multiple Layer Foam Structures 295
6.32.2.1 One-Step Process 295
6.32.2.2 Two-Step Process 296
6.32.2.3 Drop Boxes – Inside or Out? 297
6.32.2.4 Containerizing Inner Layers 298
References 299

7. Mechanical Part Design 307

7.0 Introduction 307
7.1 Design Philosophy 307
7.2 General Design Concepts 310

This page has been reformatted by Knovel to provide easier navigation.

7.3 Mechanical Design 314
7.3.1 Three-Point Flexural Beam Loading 315
7.3.2 Cantilever Beam Loading 316
7.3.3 Column Bending 317
7.3.4 Plate Edge Loading 318
7.3.5 Hollow Beam with Kiss-Off Loading 318
7.3.6 Creep 322
7.3.7 Temperature-Dependent Properties 323
7.4 Design Properties of Foams 324
7.4.1 Uniform Density Foams 324
7.4.2 Multilayer or Skin-Core Foams 329
7.5 Computer-Aided Engineering in Rotational Molding 330
7.5.1 CAD/CAM in Rotational Molding 332
7.5.2 Computer-Aided Stress Analysis 332
7.6 Some General Design Considerations 335
7.6.1 Uniformity in Wall Thickness 336
7.6.2 Shrinkage During Cooling 337
7.6.3 General Shrinkage Guidelines 339
7.6.4 Effect of Pressurization 340
7.6.5 Draft Angles and Corner Angles 341
7.6.6 Warpage Guidelines 344
7.6.7 Corner Radii – The Michelin Man 345
7.6.7.1 Right-Angled Corners 345
7.6.7.2 Acute-Angled Corners 346
7.6.8 Parallel Walls 348
7.6.9 Spacing and Bridging 348
7.6.10 Internal Threads, External Threads, Inserts, and Holes 349
7.7 Process Effects on Porosity, Impact Strength 350
7.8 Trimming 354

This page has been reformatted by Knovel to provide easier navigation.

7.9 Surface Decoration 357
7.9.1 Painting 358
7.9.2 Hot Stamping 358
7.9.3 Adhesives 358
7.9.4 In-Mold Decoration 359
7.9.5 Postmold Decoration 359
7.9.6 Internal Chemical Treatment 359
7.10 Troubleshooting and Quality Assurance 360
7.10.1 Coordinate Measuring Machine 360
References 362

Appendices 367

Appendix A. Troubleshooting Guide for Rotational Molding 367
Appendix B. Conversion Table 375

Author Index 379

Index 383

This page has been reformatted by Knovel to provide easier navigation.

1 INTRODUCTION TO ROTATIONAL MOLDING

1.0 Introduction

Rotational molding, known also as *rotomolding* or *rotocasting,* is a process for manufacturing hollow plastic products. For certain types of liquid vinyls, the term *slush molding* is also used. Although there is competition from blow molding, thermoforming, and injection molding for the manufacture of such products, rotational molding has particular advantages in terms of relatively low levels of residual stresses and inexpensive molds. Rotational molding also has few competitors for the production of large ($> 2\ m^3$) hollow objects in one piece. Rotational molding is best known for the manufacture of tanks but it can also be used to make complex medical products, toys, leisure craft, and highly aesthetic point-of-sale products.

It is difficult to get precise figures for the size of the rotational molding market due to the large number of small companies in the sector. In 1995, the North American market was estimated to be about 800 million pounds (364 ktons) with a value of US$1250 million.[1] The corresponding 1995 figure for Europe was a consumption of 101 ktons,[2] and this had risen to 173 ktons by 1998.[3] In 1997, the North American market had a value of about US$1650 million and for most of the 1990s, the U.S. market grew at 10% to 15% per year, spurred on primarily by outdoor products such as chemical tanks, children's play furniture, kayaks, canoes, and mailboxes.[4] In the latter part of the 1990s the North American market growth slowed to single figures. Independent analysts[5, 6] saw this as a temporary dip and explained it in terms of a readjustment of market sectors and increasing competition from other sectors.

Currently, the rotational molding industry is in an exciting stage in its development. The past decade has seen important technical advances, and new types of machines, molds, and materials are becoming available. The industry has attracted attention from many of the major suppliers and this has resulted in significant investment. Important new market sectors are opening up as rotational molders are able to deliver high quality parts at competitive prices. More universities than ever are taking an interest in the process, and technical forums all over the world provide an opportunity for rotational molding to take its place alongside the other major manufacturing methods for plastics.

1.1 The Process

The principle of rotational molding of plastics is simple. Basically the process consists of introducing a known amount of plastic in powder, granular, or viscous liquid form into a hollow, shell-like mold.[7–9] The mold is rotated and/or rocked about two principal axes at relatively low speeds as it is heated so that the plastic enclosed in the mold adheres to, and forms a monolithic layer against, the mold surface. The mold rotation continues during the cooling phase so that the plastic retains its desired shape as it solidifies. When the plastic is sufficiently rigid, the cooling and mold rotation is stopped to allow the removal of the plastic product from the mold. At this stage, the cyclic process may be repeated. The basic steps of (a) mold charging, (b) mold heating, (c) mold cooling, and (d) part ejection are shown in Figure 1.1.

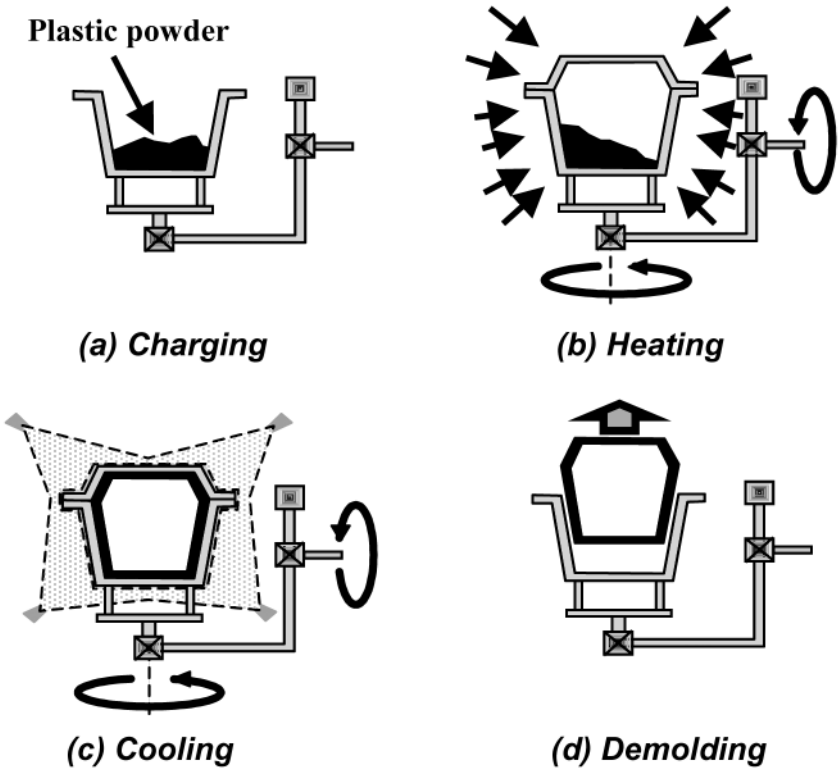

Figure 1.1 Principle of rotational molding, courtesy of The Queen's University, Belfast

Table 1.1 Typical Applications for Rotationally Molded Products

Tanks	
Septic tanks	Chemical storage tanks
Oil tanks	Fuel tanks
Water treatment tanks	Shipping tanks
Automotive	
Door armrests	Instrument panels
Traffic signs/barriers	Ducting
Fuel tanks	Wheel arches
Containers	
Reusable shipping containers	Planters
IBCs	Airline containers
Drums/barrels	Refrigerated boxes
Toys and Leisure	
Playhouses	Outdoor furniture
Balls	Hobby horses
Ride-on toys	Doll heads and body parts
Materials Handling	
Pallets	Fish bins
Trash cans	Packaging
Carrying cases for paramedics	
Marine Industry	
Dock floats	Leisure craft/boats
Pool liners	Kayaks
Docking fenders	Life belts
Miscellaneous	
Manhole covers	Tool boxes
Housings for cleaning equipment	Dental chairs
Point-of-sale advertising	Agricultural/garden equipment

Nearly all commercial products manufactured in this way are made from thermoplastics, although thermosetting materials can also be used. The majority of thermoplastics processed by rotational molding are semicrystalline, and the polyolefins dominate the market worldwide. The different types of products that can be manufactured by rotational molding are summarized in

Table 1.1. The process is distinguished from spin casting or centrifugal casting by its low rotational speeds, typically 4 – 20 revs/min. The primary competitors to rotational molding are structural blow molding and twin-sheet thermoforming.

As with most manufacturing methods for plastic products, rotational molding evolved from other technologies. A British patent issued to Peters in 1855 (before synthetic polymers were available) cites a rotational molding machine containing two-axis rotation through a pair of bevel gears. It refers to the use of a split mold having a vent pipe for gas escape, water for cooling the mold, and the use of a fluid or semifluid material in the mold to produce a hollow part. In the original patent application this was a cast white metal artillery shell. In Switzerland in the 1600s, the formation of hollow objects such as eggs quickly followed the development of chocolate from cocoa. The ceramic pottery process known today as "slip casting" is depicted in Egyptian and Grecian art, and probably predates history.

1.2 The Early Days

Rotational molding of polymers is said to have begun in the late 1930s with the development of highly plasticized liquid polyvinyl chloride, the thermoplastic competitor to latex rubber.[9–14] In addition to the ubiquitous beach balls and squeezable toys, syringe bulbs, squeezable bottles and bladders and air-filled cushions were developed during World War II. Until polyethylene powders were produced in the late 1950s, most rigid articles were manufactured from cellulosics. The early equipment was usually very crude. Generally it consisted of a hollow metal mold rotating over an open flame. Sometimes a type of slush molding would be used. In this method, the mold would be completely filled with liquid or powdered plastic and after a period of heating to form a molten skin against the mold, the excess plastic would be poured out. The molten skin was then allowed to consolidate before being cooled and removed from the mold.[15]

In the 1950s the two major developments were the introduction of grades of powdered polyethylene that were specially tailored for rotomolding,[16, 17] and the hot air oven. With the new material and equipment it was possible to rapidly advance the types of hollow plastic products that could be manufactured. In North America the toy industry took to the process in a big way and, as shown in Figure 1.2, today this sector still represents over 40% of the consumption in that part of the world.

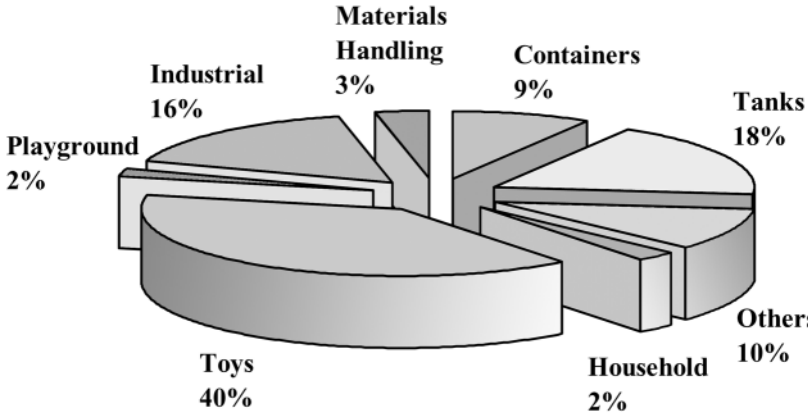

Figure 1.2 North American market sectors by product type (1999), courtesy of The Queen's University, Belfast

In Europe the nature of the market has always been different, with toys representing less than 5% of the consumption and other sectors such as containers and tanks tending to dominate (see Figure 1.3).

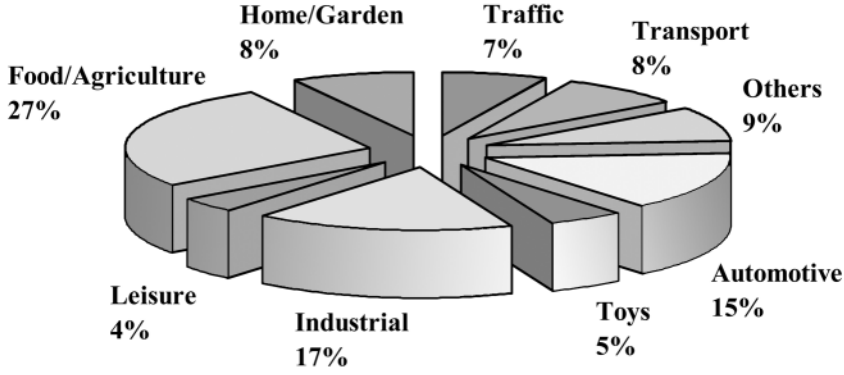

Figure 1.3 European market sectors by product type (1999), courtesy of The Queen's University, Belfast

Ever since its inception, a characteristic feature of the rotational molding industry has been its abundance of innovative designers and molders taking what is basically a very simple, and some would say crude, process and creating complex, hollow 3-D shapes in one piece. Geometry and shape have to be used particularly effectively because, the dominant polymer, polyethylene, has a very low inherent modulus and thus stiffness. In order to impart stiffness and

rigidity to the end product it is necessary to use many types of special geometrical features, many of which are unique to rotational molding. It is also necessary to encourage the plastic powder to flow into narrow channels in the mold, and this only became possible with the special grades of high quality powders developed for the process and with the additional control over heating that became available in the oven machines.

The contribution that rotational molding has made to the design of plastic products has not yet been fully appreciated by other industries. Not only has the North American toy industry produced very clever structural shapes to impart stiffness to polyethylene, geometry has also been used effectively to conceal shortcomings in the manufacturing method. The lessons learned here are only now being transferred to other technologies. In addition, special types of features, such as "kiss-off" points, have been developed by rotational molders to enhance the load carrying capacity of relatively thin walled, shell-like moldings. If rotational molding can overcome some of its disadvantages, such as long cycle times and limited resin availability, then there can be no doubt that the next 50 years will see a growth rate that will continue to track what has been achieved in the first 50 years.

1.3 Materials

Currently polyethylene, in its many forms, represents about 85% to 90% of all polymers that are rotationally molded. Crosslinked grades of polyethylene are also commonly used in rotational molding.[18,19] PVC plastisols[20–22] make up about 12% of the world consumption, and polycarbonate, nylon,[23] polypropylene,[24–27] unsaturated polyesters, ABS,[28] polyacetal,[29] acrylics,[30] cellulosics, epoxies,[31] fluorocarbons, phenolics, polybutylenes, polystyrenes, polyurethanes,[32–36] and silicones[37] make up the rest.[38] This is shown in Figure 1.4.

High-performance products such as fiber-reinforced nylon and PEEK aircraft ducts show the potential of the technology, but truly represent a very small fraction of the industry output.[39] There have also been attempts to include fibers in rotationally molded parts but there are few reports of this being done commercially.[40]

The modern rotational molding process is characterized as being a nearly atmospheric pressure process that begins with fine powder and produces nearly stress-free parts. It is also an essential requirement that the polymer withstand elevated temperatures for relatively long periods of time. Owing to the absence

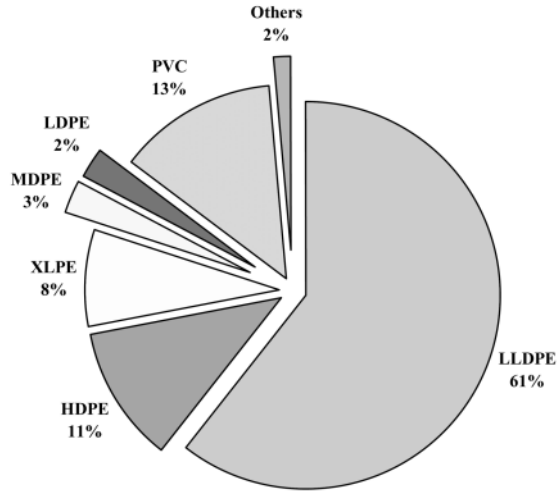

Figure 1.4 Typical usage of plastics in North American rotational molding industry,[1] information used with permission of copyright holder

of pressure, rotational molds usually have relatively thin walls and can be relatively inexpensive to fabricate. For relatively simple parts, mold delivery times can be days or weeks. Modern, multiarmed machines allow multiple molds of different size and shape to be run at the same time. With proper mold design, complex parts that are difficult or impossible to mold any other way, such as double-walled five-sided boxes, can be rotationally molded. With proper mold design and correct process control, the wall thickness of rotationally molded parts is quite uniform, unlike structural blow molding or twin-sheet thermoforming. And unlike these competitive processes, rotational molding has no pinch-off seams or weld lines that must be post-mold trimmed or otherwise finished. The process allows for in-mold decoration and in situ inserts of all types. Typical products manufactured by rotational molding are shown in Figure 1.5.

Although the rotational molding process has numerous attractive features it is also limited in many ways. The most significant limitation is the dearth of suitable materials. This is primarily due to the severe time-temperature demand placed on the polymer, but it is also due to the relatively small existing market for nonpolyolefins. Where special resins have been made available, the material prices are high, due to the development costs that are passed through to the user, and the additional cost of small-scale grinding of the plastic

granules to powder. In addition, the inherent thermal and economic characteristics of the process favor production of few, relatively large, relatively bulky parts such as chemical tanks.

Figure 1.5 Examples of rotationally molded products (paramedic box by Australian company, Sign by Rototek Ltd., U.K., Smart Bar by Team Poly Ltd., Adelaide, Australia)

Part designers must adjust to the generous radii and relatively coarse surface textures imposed by the process. Furthermore, the process tends to be labor intensive and until recently, the technical understanding of the process lagged behind those of other processes such as blow molding and thermoforming. Part of the reason for this is that, unlike nearly every other manufacturing method for plastic parts, the rotational molding process relies on coalescence and densification of discrete powder particles against a rotating mold cavity wall, an effect that is extremely difficult to model accurately. Another part of the reason is that the process has not attracted academic interest in the same way as other processes such as compounding, extrusion, and injection molding.

Probably the greatest limitation has been the general opinion that rotational molding is a cheap process, and therefore, by implication, one that produces parts of lesser quality than those made by other processes. Unfortunately,

in the past, rotational molders did not discourage this opinion. This situation is now changing and the Association of Rotational Molders (ARM) formed in 1976 has been instrumental in acting as the focal point for many important advances in the industry. A number of other similar organizations have also been set up in Europe and Australasia. Traditionally this sector has been dominated by small companies, which by their nature must focus on their own short-term needs. ARM has acted as a voice for the industry, providing opportunities to pool resources to fund R & D, and to promote the industry. These efforts have undoubtedly helped rotational molding to become the fastest growing sector of the plastics processing industry. In 2000, the Society of Plastics Engineers (SPE) chartered the Rotational Molding Division in order to promote greater technical discussions about the process. This will result in a larger number of academic institutions taking an interest in the process, which has to be good for the future advancement of rotational molding.

1.4 Advantages and Disadvantages

The main attractions of rotational molding are:

- A hollow part can be made in one piece with no weld lines or joints
- The end product is essentially stress-free
- The molds are relatively inexpensive
- The lead time for the manufacture of a mold is relatively short
- Short production runs can be economically viable
- There is no material wastage in that the full charge of material is normally consumed in making the part
- It is possible to make multilayer products
- Different types of product can be molded together on the one machine
- Inserts are relatively easy to mold in
- High quality graphics can be molded in

The main disadvantages of rotational molding are:

- The manufacturing times are long
- The choice of molding materials is limited
- The material costs are relatively high due to the need for special additive packages and the fact that the material must be ground to a fine powder
- Some geometrical features (such as ribs) are difficult to mold

Table 1.2 compares the characteristics of the processes that can be used to make hollow plastic products.

Table 1.2 Comparison of Blow Molding, Thermoforming, and Rotational Molding (Adapted from Ref. 41.)

Factor	Blow Molding	Thermo Forming	Rotational Molding
Typical product volume range (cm^3)	10^1–10^6	5×10^0–5×10^6	10^1–10^8
Plastics available	limited	broad	limited
Feedstock	pellets	sheet	powder/liquid
Raw material preparation cost	none	up to +100%	up to 100%
Reinforcing fibers	yes	yes	yes, very difficult
Mold materials	steel/ aluminum	aluminum	steel/ aluminum
Mold pressure	<1 MPa	<0.3 MPa	<0.1 MPa
Mold cost	high	moderate	moderate
Wall thickness tolerance	10%–20%	10%–20%	10%–20%
Wall thickness uniformity	tends to be nonuniform	tends to be nonuniform	uniformity possible
Inserts	feasible	no	yes
Orientation in part	high	very high	none
Residual stress	moderate	high	low
Part detailing	very good	good, with pressure	adequate
In-mold graphics	yes	possible	yes
Cycle time	fast	fast	slow
Labor intensive	no	moderate	yes

1.5 General Relationships between Processing Conditions and Properties

The rotational molding process is unique among molding methods for plastics in that the plastic at room temperature is placed in a mold at approximately room temperature and the whole assembly is heated up to the melting temperature for the plastic. Both the mold and the plastic are then cooled back to room temperature. Normally, the only controls on the process are the oven temperature, the time in the oven, and the rate of cooling. Each of these variables has a major effect on the properties of the end product and this will be discussed in detail in later chapters. At this stage it is useful to be aware that if the oven time is too short, or the oven temperature is too low, then the fusing and consolidation of the plastic will not be complete. This results in low strength, low stiffness, and a lack of toughness in the end product. Conversely, if the plastic is overheated then degradation processes will occur in the plastic and this results in brittleness.[42–44] In a commercial production environment the optimum "cooking" time for the plastic in the oven often has to be established by trial and error.[45] In recent years it has been shown that if the temperature of the air inside the mold is recorded throughout the molding cycle, then it is possible to observe in real time many key stages in the process.[46, 47] This technology will be discussed in detail in Chapter 5. At this stage an overview will be given of the relationships between processing conditions and the quality of the molded part.

It is important to understand that rotational molding does not rely on centrifugal forces to throw the plastic against the mold wall. The speeds of rotation are slow, and the powder undergoes a regular tumbling and mixing action. Effectively the powder lies in the bottom of the mold and different points on the surface of the mold come down into the powder pool. The regularity with which this happens depends on the speed ratio, that is the ratio of the major (arm) speed to the minor (plate) speed. The most common speed ratio is 4:1 because this gives a uniform coating of the inside surface of most mold shapes. The importance of the speed ratio in relation to the wall thickness distribution will be discussed in Chapter 5.

When the mold rotates in the oven, its metal wall becomes hot, and the surface of the powder particles becomes tacky. The particles stick to the mold wall and to each other, thus building up a loose powdery mass against the mold wall. A major portion of the cycle is then taken up in sintering the loose powdery mass until it is a homogeneous melt.[48–50] The irregular pockets of

gas that are trapped between the powder particles slowly transform themselves into spheres and under the influence of heat over a period of time they disappear. These pockets of gas, sometimes referred to as bubbles or pinholes, do not move through the melt. The viscosity of the melt is too great for this to happen, so the bubbles remain where they are formed and slowly diminish in size over a period of time.[51–55]

Molders sometimes use the bubble density in a slice through the thickness of the molding as an indication of quality. If there are too many bubbles extending through the full thickness of the part then it is undercooked. If there are no bubbles in the cross section then it is likely that the part has been overcooked. A slice that shows a small number of bubbles close to the inner free surface is usually regarded as the desired situation.

Other indications of the quality of rotationally molded polyethylene products relate to the appearance of the inner surface of the part and the smell of the interior of the molding. The inner surface should be smooth with no odor other than the normal smell of polyethylene. If the inner surface is powdery or rough then this is an indication that the oven time was too short because insufficient time has been allowed for the particles to fuse together. If the inner surface has a high gloss, accompanied by an acrid smell then the part has been in the oven too long. Degradation of the plastic begins at the inner surface due to the combination of temperature and air (oxygen) available there.[56–60]

Even if the oven time is correct, the method of cooling can have a significant effect on the quality of the end product. The most important issue is that, in rotational molding, cooling is from the outside of the mold only. This reduces the rate of cooling and the unsymmetrical nature of the cooling results in warpage and distortion of the molded part.[61-63] The structure of the plastic is formed during the cooling phase and rapid cooling (using water) will result, effectively, in a different material compared with slow cooling (using air) of the same resin. The mechanical properties of the plastic will be quite different in each case. Slower cooling tends to improve the strength and stiffness of the plastic but reduces its resistance to impact loading. Fast cooling results in a tougher molding but it will be less stiff. The shape and dimensions of the part also will be affected by the cooling rate.

This brief introduction to the interrelationships between processing and properties emphasizes the importance of understanding the *technology of rotational molding*. Although it appears to be a simple process, there are many

complex issues to be addressed. The molder needs to understand what is happening at each stage in the process and more importantly, it is crucial to realize that control can be exercised over, not just the manufacturing times, but the quality of the end product. The technology of rotational molding is now at an advanced stage and it is possible to quantify what is happening at all stages of the process. The following chapters describe in detail the various aspects of the process and wherever possible an attempt has been made to provide quantitative estimates of the relative effects of the process variables.

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2 ROTATIONAL MOLDING POLYMERS

2.0 Introduction

Of the millions of tons of plastics used in the world every year, about 80% are thermoplastic and 20% are thermosetting. Thermosetting polymers are those that undergo chemical changes during processing such that the final molecular structure is three-dimensional. Thermosetting polymers are likened to boiling an egg. Once the egg becomes hard, it cannot be softened again by reheating. Polyurethanes, polyesters, and phenolics are thermosetting polymers that have been rotationally molded at times. The final molecular structure of thermosetting polymers is such that they cannot be reused or recycled with conventional means.

When thermoplastic polyers are processed, the final molecular structure is essentially the same as the original molecular structure. Thermoplastic polymers are likened to spaghetti pasta. When the pasta is cold, the strands are immobile, but when it is hot, the strands can easily slide over one another. Also the pasta can be repeatedly cooled and reheated. Polyethylene, polypropylene, polystyrene, and polyvinyl chloride are the most common thermoplastic polymers and are frequently called commodity polymers. Engineering polymers typically have higher performance criteria and are generally more expensive than commodity polymers. Nylon, acrylonitrile-butadiene-styrene (ABS), and polycarbonate (PC) are typical engineering polymers. High-performance polymers generally have properties superior to engineering polymers and are also more expensive. Fluoroethylene polymer (FEP) and polyether-ether ketone (PEEK) are typical high-performance polymers. So long as processing has not mechanically damaged the thermoplastic polymer structure, these polymers are considered reusable and recyclable.

2.1 General Characteristics of Polymers

Polyethylene is thermoplastic and dominates the rotational molding industry. In addition, crosslinked polyethylene has found wide acceptance in rotational molding, for reasons detailed below. Crosslinking is the activation and subsequent linking of polyethylene chains using either electron beam irradiation or chemicals. The final structure is essentially three-dimensional, with crosslinks occurring every 500 to 1000 backbone carbon atoms. Although this crosslinking level is very low compared with phenolics, where crosslinks occur every 10 backbone carbon atoms, the final molecular structure is indeed three-dimen-

sional. As a result, crosslinked polyethylene (XLPE) is usually considered to be unrecyclable. The general chemical makeup and typical physical properties of polymers are found in standard reference books.*

All polymers exhibit glass transition temperatures. The glass transition temperature (T_g) is defined as the temperature at or above which the molecular structure exhibits macromolecular mobility. Typically this is when fifty carbons along the molecular chain can move in concert. More practically, it is defined as the temperature range where the molecular structure is transformed from being a brittle solid to being a ductile or rubbery solid. Thermoplastic polymers are generally of two morphological types. Amorphous polymers, such as PVC, ABS, and polycarbonate, are characterized as having no crystalline structure or crystalline order. Amorphous thermoplastic polymers and essentially all thermosetting polymers have only one thermodynamic transition, the glass transition. Thermoplastic polymers simply get softer and softer as the temperature is raised above T_g. Crystalline polymers, on the other hand, have ordered molecular structure above T_g. As seen in Table 2.1, crystalline levels vary from about 20% for polyethylene terephthalate, to 70% for polypropylene, to as high as 98% for polytetrafluoroethylene (PTFE) fluoropolymer. The molecular structure of a crystalline polymer is for the most part, dictated by its crystalline structure or morphology. As an example, polyethylene has a glass transition temperature of about -100°C and a melting temperature or T_m of about 135°C. The crystalline structure of polyethylene allows parts to retain their shapes at boiling water temperatures or more than 200°C above its T_g.

Table 2.1 Level of Crystallinity in Selected Polymers

Polymer	Condition	Crystallinity [%]
LDPE	All	40–50
LLDPE	All	60
HDPE	All	60–80
Polypropylene (PP)	Rapidly cooled	45–50
Nylon 6 (PA6)	Slowly cooled	40–50
Nylon 6 (PA6)	Quenched	10
Polyethylene Terephthalate (PET)	Slowly cooled	20–30
Polyethylene Terephthalate (PET)	Quenched	0–10

* The reader should become familiar with References 1–3a.

As noted earlier, until the development of polyethylene, rotational molding focused on polyvinyl chloride or PVC plastisols and powdered cellulosics. According to a recent survey, Table 2.2, the following polymers were used by U.S. rotational molders.[4]

Table 2.2 Rotational Molding Materials Use [1996]

Polymer	Percent of Molders
LDPE	86
LLDPE	69
HDPE	33
Polypropylene	22
Nylon (All Types)	21
Polycarbonate	20
PVC (All Types)	25

It is apparent that polyolefins dominate the current rotational molding process. The most obvious reasons for this domination are chemical and UV resistance, ability to withstand the long time-temperature environment of the process, and their relatively low material costs. Nevertheless, it is equally apparent that polyolefins cannot provide high temperature thermal stability, creep resistance, surface hardness, and other properties provided by nonolefins such as styrenics and thermosets.

This section reviews some of the characteristics of polymers that are currently molded. Certain mechanical and chemical tests used to screen polymers and determine final part properties are detailed. The section does not consider some of the esoteric polymers such as polyether-ether ketone and polyimides or some thermally sensitive polymers such as rigid polyvinyl chloride. Furthermore, this section does not review the polymer response to the rotational molding thermal environment. This is covered later in the book.

2.2 Polymers as Powders and Liquids

The principal form for the vast majority of polymers used in rotational molding is as -35 mesh powder. Nearly all thermoplastic polymers are available as powders or as grindable pellets. As noted below, liquid polymers offer more modest forming conditions.

2.3 Polyethylene Types

Polyethylene (PE) is a chemically simple molecule:[5]

$$CH_3–CH_2–(–CH_2–CH_2–)_x–CH_2–CH_3$$

When x is on the order of 50, the molecule is a high-temperature wax. When x is on the order of 500, the polymer is a low-molecular weight polyethylene, having a melting point around 120°C. When x is around 2500, the polymer is a high-molecular weight crystalline polyethylene, having a melting point around 135°C and a room temperature density of about 950 kg/m^3. When x is around 250,000, the polymer is *ultra-high molecular weight polyethylene* (UHMWPE), with a melting temperature of about 137°C and a room temperature density of about 965 kg/m^3. As an example, the molecular weight of a typical rotational molding grade high-density polyethylene (HDPE) is about 35,000 or x is about 1250, with a nominal density of usually about 950 kg/m^3.

2.3.1 *Low-Density Polyethylene*

In addition to density, polyethylenes are characterized by the extent of branching, Figure 2.1.[3a] *Low-density polyethylene* (LDPE), sometimes referred to as *high-pressure polyethylene* or *branched polyethylene*, has extensive side chains, up to perhaps 100 ethylene units in length. The long branches tend to inhibit molecular organization during cooling. As a result, LDPEs typically have relatively low densities of 910 kg/m^3 to 925 kg/m^3 or so and relatively low crystallinities of 45% to 66%. LDPEs are relatively soft polyethylenes, with flexural modulus ranges of 0.24 to 0.35 GPa (35,000 to 50,000 lb/in^2) and a Shore D hardness range of 46 to 52. Owing to the high number of tertiary hydrogens, LDPE does not have good environmental stress crack resistance (ESCR). According to ASTM D-1693, LDPE survives about 1 hour in 10% Igepal without cracking. Since the primary use for LDPEs is in blown film, LDPEs are typically formulated to have relatively high melt indexes of 10 or more.* These high MIs exacerbate the relatively poor mechanical properties. Nevertheless, LDPEs mold well at low temperatures and yield parts with surfaces that accurately replicate mold surfaces.

* Melt index or MI is described below.

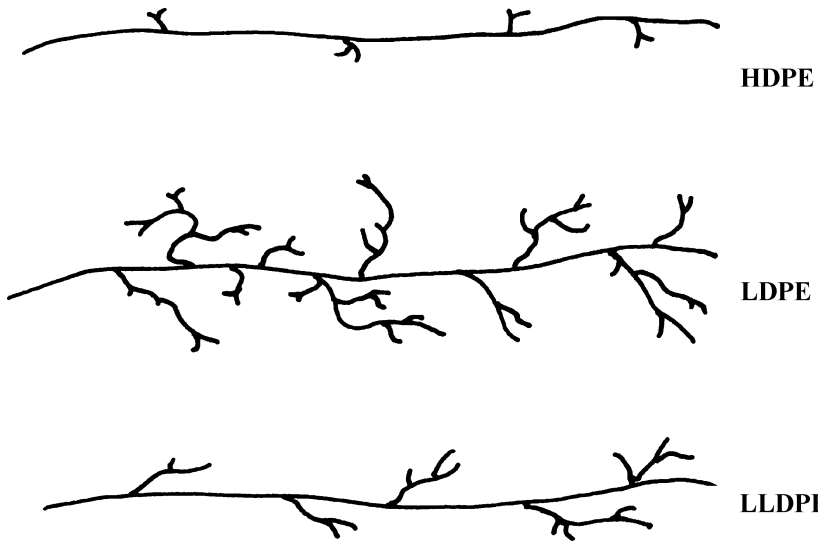

Figure 2.1 Molecular chain characteristics of three common polyethylenes, redrawn from Ref. 3a, with permission of Hanser Verlag, Munich

2.3.2 *Medium-Density Polyethylene*

Medium-density polyethylene (MDPE), is usually preferred over LDPE for many applications requiring strength or stiffness in addition to ease of processing. MDPE is characterized by fewer and shorter side chains than LDPE. As a result, MDPEs typically have densities in the range of 925 kg/m^3 to 940 kg/m^3 or so and crystallinities in the range of 55% to 75%. MDPEs are somewhat stiffer than LDPEs, with flexural modulus ranges of 0.69 to 0.90 GPa (100,000 to 130,000 lb/in^2) and a Shore D hardness range of 52 to 56. MDPEs have superior ESCRs when compared with LDPE with the typical time of survival in 10% Igepal of 1000 hours or more. MDPEs are normally formulated for injection molding and so the melt indexes range from 1 to perhaps 20. MDPEs mold well at temperatures higher than LDPEs, densify fully and seem to have fewer surface blemishes and lower porosity than HDPEs. Rotationally molded parts from MDPEs tend to have matte surfaces.

2.3.3 *High-Density Polyethylene*

High-density polyethylene (HDPE), also known as *linear polyethylene* or *low-pressure polyethylene,* is the preferred polyethylene for chemical containers of all sizes, primarily due to its exceptional environmental stress crack resistance. It can survive for more than 1000 hours in 10% Igepal, and it has excellent stiffness from room temperature to the boiling point of water. The flexural modulus range for HDPE is 0.93 to 1.52 GPa (135,000 to 220,000 lb/in^2) and its Shore D range is 60 to 66. Even though HDPE is frequently called linear polyethylene, it still has some short chain branching. Nevertheless, its linear nature and its high backbone mobility allow it to crystallize to 75 to 90% of theoretical. The crystalline structure is characterized as predominantly spherulitic. That is, the formed crystallite is spherical with a quiescent diameter of 50 microns or more. Since these crystallites are much greater than the wavelength of visible light (0.4 to 0.7 microns), they cause the product to have a milky, translucent appearance. Since the crystallite is more ordered and more tightly packed than the amorphous phase, the density of HDPE is typically around 960 kg/m^3, approaching the theoretical value of 1000 kg/m^3. Many HDPEs are formulated for extrusion and blow molding applications and as a result, there are many fractional melt indexes. Void-free rotationally molded parts are usually achieved with HDPE melt indexes in the range of 2 to 10 or so.

Frequently, the proper grade of HDPE is characterized in terms of melt index or MI, ASTM D-1238. Melt index is determined by squeezing HDPE at 190°C through a calibrated-diameter hole at a calibrated force of 2.16 kg, and measuring the weight of extrudate over a predetermined period of time. The detailed melt index test is given below. The extrudate weight in grams is the melt index or MI. The melt index is proportional to the reciprocal of the polymer molecular weight:

$$MI \propto 1/MW \quad \text{or} \quad MI = A/MW \tag{2.1}$$

where A is a proportionality constant that is specific for a homologous series of polyethylenes. The MI is used to group polyethylenes according to the type of process. For example, MIs of 10 to 30 or more are recommended for high-flow injection molding. MIs of about 1 are recommended for extrusion. Fractional MIs of about 0.2 to 0.8 are recommended for blow molding and MIs of 2 to 10 or so are recommended for rotational molding. Polymer properties are dependent on molecular weight of a homologous series, as shown below, Table 2.3.

Table 2.3 Property Changes with Increasing MI[6]

Property	Change
Barrier properties	No trend
Bulk viscosity	Decreasing
Chemical resistance	Decreasing
Creep resistance	No trend
Ductility	Decreasing
Ease of flow	Increasing
ESCR	Decreasing
Flexural modulus	Decreasing
Hardness	No trend
Impact strength	Decreasing
Molecular weight	Decreasing
Stiffness	No trend
Tensile strength	Decreasing
Weatherability	Decreasing

The effect of polyethylene density on polymer properties is shown in Table 2.4.

Table 2.4 Property Changes with Increasing Polyethylene Density[6]

Property	Change
Barrier properties	Increasing
Chemical resistance	Increasing
Creep resistance	Increasing
Ductility	Decreasing
ESCR	Decreasing
Hardness	Increasing
Heat deflection	Increasing
Impact strength	Decreasing
Optical properties	Decreasing
Shrinkage	Increasing
Stiffness	Increasing
Tensile strength	Increasing
Weatherability	No trend

2.3.4 *Linear Low-Density Polyethylene*

Linear low-density polyethylene (LLDPE) has side chains similar to those of LDPE but, with proper catalysts and coreactive agents,* the chain lengths

* Typically, 1-butene, 1-hexene, or similar alpha-olefins.

are dramatically reduced in length.* This hybrid polyethylene is compared in Figure 2.1 with HDPE and LDPE. LLDPE has a density range of 910 kg/m^3 to about 940 kg/m^3, and is 65% to 75% crystalline at room temperature. It has improved stiffness, chemical resistance, and tensile strength, but somewhat poorer impact strength when compared with LDPE and MDPE. The flexural modulus range for LLDPE is 0.42 to 0.83 GPa (60,000 to 120,000 lb/in^2) and a Shore D hardness range of 50 to 56. LLDPE does not have the ESCR characteristics of HDPE, usually lasting for only a few hours in 10% Igepal.** LLDPE is formulated for a variety of applications including blown film and injection molding and so its melt index range is quite large, from fractional to 20 or more. Although LLDPE seems to coalesce*** well, porosity can be a problem in certain instances, indicating that densification may not proceed as completely as with homopolymer polyethylenes. In many respects, LLDPE is an "in-between" polymer in that its mechanical properties are somewhat inferior to HDPE and its moldability is somewhat less than LDPE and MDPE. It is also more expensive than the classic homopolymers. Nevertheless, it is sought for its excellent high-temperature strength of about 200°F or 100°C, as measured by ASTM D-348.

Recently, substantial effort by several resin suppliers such as Dow, Exxon, Montel, BP Amoco, and others, has focused on advanced or fourth-level Ziegler-Natta catalysts or *metallocene catalysts*. Polyolefins produced by these catalysts yield a very rich array of new polymer types. Although metallocene polyethylenes are technically feasible and commercially available, albeit at a premium, most of the development effort has focused on polypropylene and thermoplastic elastomers. Insofar as metallocene polyethylenes are concerned, it appears that they are tougher and have better chemical resistance than LLDPE, but it also appears that the current grades exhibit greater resistance to flow. This implies that the current grades may not sinter as well as LLDPE, which doesn't sinter as well as either HDPE or LDPE. As of this writing, the rotational molding characteristics of metallocene polyethylenes have yet to be fully evaluated.

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* Be aware that although LLDPE and MDPE have essentially the same density range, to wit, 925 kg/m^3 to 940 kg/m^3, LLDPE is *not* MDPE. MDPE is characterized by fewer long chain branches per 100 ethylene units than LDPE and by side chains that are dramatically longer than those of LLDPE. Furthermore, LLDPE is in essence a copolymer, not a homopolymer like LDPE, MDPE, and HDPE.

** Typically, LLDPEs with lower comonomer concentrations have improved ESCRs.

*** Throughout this work, the fusing together of powder particles will be referred to as either "coalescence," being a more precise technical description of the fusion process, or "sintering," being a term adapted from powder metallurgy and found extensively throughout older literature.

Even though HDPE has excellent chemical resistance, it is still attacked by hydrocarbons, notably gasoline, and other chemicals such as esters and halogenated hydrocarbons. In addition, polyethylene has notoriously poor creep resistance. When chemical tanks or drum liners are required, or when large, unsupported liquid containers are needed for long-term storage, the polyethylene is frequently chemically crosslinked. Crosslinking prevents molecules from sliding over one another over long times, thus minimizing creep and greatly increasing stress crack resistance to greater than 1000 hours in 10% Igepal. For HDPEs, the chain is immobilized every 1000 backbone carbons or so. For LDPEs, the crosslink density is higher, to perhaps every 250 backbone carbons. Typically, MDPEs and LLDPEs are strong candidates for crosslinking. A typical crosslinked polyethylene has a density range of 925 kg/m^3 to 940 kg/m^3 or so, a flexural modulus range of 0.5 to 1.0 GPa (70,000 to 140,000 lb/in^2) and a Shore D hardness range in the mid-50s. The crosslinking agent, usually a peroxide such as dicumyl peroxide or benzoyl peroxide, is added to the polymer by the resin supplier. Reaction typically takes place during the curing portion of the heating cycle, after the polymer powder has coalesced and densified into a monolithic layer against the mold surface. ASTM D-2765 is the standard test for determination of extent of crosslink in a rotationally molded polyethylene part. In short, a weighed sample of the polymer is placed in a 100-mesh stainless steel wire cage that is suspended in 140°C refluxing xylene for 4 to 12 hours. The cage containing the gelled polymer is then vacuum-dried at 65°C for 4 to 12 hours and then weighed. The extent of crosslinking is the ratio of weights, before and after.* It is well-known that significant changes in the characteristics of polyethylene are achieved only when gel content exceeds about 50%,[7] and for rotational molding, gel content of 70% to 80% is recommended. The detailed gel content test is given below.

2.3.5 *Ethylene Vinyl Acetate*

When vinyl acetate is block-copolymerized with ethylene, the result is *ethylene vinyl acetate* (EVA):

$$-(-CH_2-CH_2-)_x-(-CH_2-CHOOCCH_3-)_y-$$

where x represents the block length of the ethylene mer and y represents the block length of the vinyl acetate mer. Typically EVAs incorporate 5 to 50%

* Note that to achieve an accurate gel fraction, the weights of inorganics such as fillers and pigments used with the polyethylene, must be subtracted from the before and after weights.

vinyl acetate. Increasing vinyl acetate concentration results in decreasing crystallinity, increasing ductility, and decreasing tensile strength. Typical EVA densities are 930 to 950 kg/m^3. EVA melt temperatures range from 90°C to as much as 120°C and decrease with increasing vinyl acetate content. Depending on the copolymer ratio, EVA has a Shore D hardness range from the low 40s to 55 or so. Although EVAs are not normally sought for their ESCR, they are considered to be superior to LDPE in such aggressive environments as 10% Igepal. EVA has been rotationally molded into products such as hollow gaskets and bladders. EVA is easily closed-cell foamed to relatively low densities with many common chemical blowing agents (CBAs).[1] As a result, foamed EVA finds use in shock mitigation and flotation applications such as boat and pier bumpers, life vests, buoys, and marine craft seating.

2.4 Polypropylene

Polypropylene[*] or PP is a commodity crystalline polymer that has a high (165°C) melt temperature, is about 60% crystalline and has a very low room temperature density of 910 kg/m^3. It has excellent room temperature flexibility, leading to the concept of "living hinge," and has superior chemical resistance, particularly to soaps and cleaning and sterilizing agents, with ESCR survival of more than 1000 hours in 10% Igepal. Its chemical structure is:

$$-(-CH_2-\underset{\displaystyle CH_3}{\underset{|}{CH}}-)_x-$$

PP is stereospecific. There are three molecular conformations for PP. When the methylene group, $-CH_3$, occurs randomly on one side or the other of the main chain, the polymer does not crystallize, remains a rubber, and is called *atactic*. When the methylene group appears always on the same side of the main chain, the polymer is called stereospecific, it crystallizes, and is called *isotactic* (iPP). When the methylene group alternates from one side of the main chain to the other, the polymer is called *syndiotactic* (sPP). Commercial rotational molding grade PPs are about 95% isotactic polypropylene. The melt viscosity of polypropylene is quite low. Melt flow indices[**] (MFIs), are typically in the range of 3 to perhaps 300, with rotational molding grades being in the range of 5 to 10. Polypropylene homopolymer flexural modulus

[*] An excellent general reference on polypropylene is Maier and Calafut.[8]

[**] The ASTM D-1638 melt index test is run at 230°C for PP rather than 190°C for polyethylenes. The test is called MFI for PP, to distinguish it from the MI for polyethylene.

range is 1.2 to 1.4 GPa (175,000 to 200,000 lb/in^2), or almost to the level of HDPE. The hardness range of PP tends to be slightly less than that for HDPE.

Even though iPP has a high melting temperature, unstabilized PP exhibits a very high oxidative degradation rate at temperatures of about 100°C. While this problem can be minimized through thermal stabilizers and antioxidants, it remains a problem for long-term, high temperature performance of PP products, and for recycling of PP trim. While iPP has greater chemical resistance than HDPE, it has poorer UV resistance. UV stabilizers minimize this problem. Even more serious, the glass transition temperature of iPP is about 0°C. In other words, iPP is approaching a brittle condition even at room temperature. Copolymers of PP with polyethylene overcome some of these problems, but PP copolymers tend to have lower MFIs, are softer, have lower chemical resistance than iPP homopolymers, and are substantially more expensive than homopolymers. Oxygen and UV sensitivity are somewhat minimized, but antioxidants and UV stabilizers are still required. The effect of copolymer concentration on PP properties is shown in Table 2.5.

Table 2.5 Effect of Increasing Copolymer Concentration for Polypropylene

Property	**Change**
Chemical resistance	Decreasing
Flexural modulus	Decreasing
Glass transition temperature	Decreasing
Hardness	Decreasing
Heat deflection temperature	Decreasing
Impact strength	Increasing
Low-temperature toughness	Increasing
Stiffness	Decreasing
Tensile strength	Decreasing

The mechanical properties of PP are frequently enhanced with fillers. For example, 40% talc doubles the room temperature modulus of PP. Calcium carbonate at the same loading increases it only 50%, but does not reduce its ductility or toughness as much as talc. Both additives opacify PP. Talc yields a gray-white opaque PP, whereas calcium carbonate yields a yellow-white opaque PP. Both are available as rotational molding powders.

Probably the major limitation to the use of copolymers of polypropylene in rotational molding is the poor high-temperature stability. In addition, PP in

general has inherently poor scratch resistance and recrystallizes very slowly, thus inviting warpage and distortion during the cooling step.*

2.5 PVC — Plastisols, Drysols, and Powdered Flexible Compounds

Polyvinyl chloride (PVC) as been known since the 1800s as a brittle, intractable, amorphous polymer that has very poor thermal stability in the presence of oxygen.** It can be produced in crystalline form but all commercial grades are amorphous. The structure is:

$$-(-CH_2-CHCl-)_x-$$

In the early 1920s, Waldo Semon at BFGoodrich found that the PVC molecule could be solvated by many organics, particularly phthalates and phosphates.*** In addition, heat stabilizers based on heavy metals and now on zinc and tin, were developed to provide increasing processing life for the polymer. To meet specific needs, other additives such as lubricants, extenders, fillers, impact modifiers, and pigments are added to the PVC compound, in addition to heat stabilizers and plasticizers. Today, it is estimated that more than 60% of all the adducts used in plastics are used in PVC compounds. Although the earliest PVC compounds were produced as emulsions, essentially all PVC compounds are produced today as suspensions. Suspension compounds contain essentially no emulsifiers and are considered to be more processable. Liquid PVC compounds are called *plastisols* and typically have room-temperature viscosities of less than 10,000 cp. Products made from plastisols have Shore Durometers of 55A and less, to perhaps as low as 30A, and they can have characteristic skin- or leather-like appearance and feel.****

With certain recipes, the plasticizer is sufficiently absorbed by the PVC compound that the resulting product is a dry, granular powder called a *drysol*. During rotational molding, the drysol must remain freely flowing throughout the first portion of heating as the temperature of the mold is increasing.

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* Recrystallization kinetics are discussed in detail in the cooling section of Chapter 6.

** According to H. Morawetz,[9] P.E.M. Berthelot was the first scientist to describe the polymerization of vinyl compounds in 1863, although V. Regnault had identified a solid intractable mass of polymerized vinylidene chloride in 1838. E. Baumann in 1872 produced a chalky useless mass that he identified as PVC.

*** According to H. Morawetz,[10] F. Klatte, Ger. Pat. 281877, described plasticization of PVC in 1913. The technology was not pursued in Germany until the late 1920s.

**** More details on liquid PVCs are given in Section 2.8.

Excessive bridging and roller formation may occur if the drysol becomes prematurely tacky. Furthermore, drysol must remain freely flowing even in hot, humid plant conditions. And it must not compression-cake in bags and gaylords. Typically, drysols have Shore Durometers in excess of 55A.

Traditional high-speed dry-blending devices are unable to make a freely flowing powder having a Durometer of 55A or less. As a result, drysols are used to produce semiflexible products. Recently, compound recipes have been developed that allow the production of nontacky, freely flowing micropellets by extrusion. These micropellets are positioned to replace both drysol powders and plastisols, offering less clean up and easier disposal than unused powders and liquids. One of the primary advantages to PVC micropellets is that much higher molecular weight PVC can be used to produce a low-Durometer product having higher tensile and tear strengths.*

2.6 Nylons

Nylons or properly, poly-α-aminoacids or polyamides, are condensation polymers, produced from dibasic acids and difunctional amines, by the elimination of water. The two chemical forms for the polymer class are:

First: $-NH-(-CH_2-)_z-CO-$

Second: $-NH-(-CH_2-)_x-NH-CO-(-CH_2-)_y-CO-$

In the first form, the monomer contains both acid and amine groups and z represents the number of methyl groups in the monomer. In the second form, x represents the number of methyl mers in the amine monomer and y represents the number of methyl mers in the acid monomer. The various types of polyamides are shown in Table 2.6.

The reaction to produce polyamides is reversible. Nylon, like all condensation polymers, has an affinity to water in any form. As a result, nylon powder must be extensively dried prior to dispensing in the mold. It is recommended that the powder be melted and densified in an inert atmosphere.** Powders are usually shipped in polyethylene bags that are sometimes metallized.

* Although micropellet technology is a relatively new technology that can be used for any extrudable polymer, it has found its first major market in PVCs. Please see the section on micropellet technology in Section 3.9.

** This can be achieved by adding pieces of dry ice or solid CO_2 to the powder in the mold just before closing the mold, or by continuous nitrogen blanketing of the powder and formed part during molding.

Table 2.6 Nylon Types

Commercial Notation	*z*	*x*	*y*	Rotationally Moldable
Nylon 6 or caprolactam	5	—	—	yes
Nylon 11	10	—	—	yes
Nylon 12	11	—	—	yes
Nylon 66	—	6	4	difficult
Nylon 610	—	6	8	no
Nylon 612	—	6	10	no

Polycaprolactam (PA-6) is also available in liquid form. Although it is used primarily in reaction injection molding processes, it is also rotationally moldable at relatively low oven temperatures. When caprolactam or oligomeric polycaprolactam is used as the starting moiety, catalysts and other processing aids are added to initiate and continue polymerization. Since caprolactam is a difunctional molecule, polymerization occurs as chain extension, resulting in a linear thermoplastic polymer. Polyamides are crystalline, to as much as 50%. However, the rate of crystallization is very slow when compared with polyethylenes.* As a result, nearly amorphous polyamide films can be made by rapid quenching. Crystalline polyamides have very high melt temperatures and excellent resistance to chemicals, in particular to hydrocarbons, including lubricating oils, brake and transmission fluids, diesel fuels, and gasoline. For example, PA-6 has a flexural modulus range of 1.4 to 2.8 GPa (200,000 to 400,000 lb/in^2) and an ASTM D-648 heat deflection temperature of 175°C. Polyamide melt temperatures are given in Table 2.7.

Table 2.7 Polyamide Melt Temperature

Polyamide	Melt Temperature, °C
66	265
6	215
610	215
612	210
11	185
12	175

As noted, nylon 6, 66, 11, and 12 can be pulverized for rotational molding. Melt viscosities of most nylons are very low, allowing the polymer to freely flow even under gravitational force.** Care must be taken in ensuring that

* Recrystallization kinetics are reviewed in Chapter 6.

** Once the nylon is fully molten, higher than normal arm speeds are sometimes necessary to minimize local sagging, thinning, and even "glopping" or dripping.

the molten polymer does not pull away from the mold during heating and the early stages of cooling. The reader should also review Section 2.8.2 for information on rotational molding of liquid nylons.

2.7 Other Polymers

Thermal stability at elevated temperature and extended time is a primary requisite for polymers in rotational molding. As noted earlier, the family of polyethylenes, with their inherent thermal stability, represent the majority of polymers that are rotationally molded, by far. Nevertheless, in addition to flexible vinyls and nylons, other polymers have been rotationally molded, albeit with greater difficulties.

2.7.1 *Polycarbonate*

Polycarbonate (PC) is a tough, higher temperature amorphous polymer that is naturally transparent. Its chemical nature is shown below. Polycarbonate has impact strength rivaled only by LDPE, a flexural modulus range of 2.1 to 2.6 GPa (300,000 to 375,000 lb/in^2), and a heat distortion temperature of 135°C.

$$-(-O-\Phi-\underset{\displaystyle CH_3}{\overset{\displaystyle CH_3}{\overset{|}{\underset{|}{C}}}}-\Phi-O-CO-)_x-$$

where the Φs are the main chain benzene rings. Polycarbonate, like nylon, is a condensation polymer. As a result it has a great affinity for water in any form. As a result, PC in powder form must be dried for up to four hours at 150°C prior to molding, and powder transfer from the weighing station to the mold filling station must be done very quickly to minimize moisture absorption. Recommended drying times for moisture-sensitive polymers are given in Table 2.8. Processing under nitrogen blanket is also strongly recommended. Preheated molds are recommended for critical, high-impact parts such as lighting globes. Dry-powder coloring is possible with PC. However, for uniform coloration, it is recommended that precolored pellets be pulverized just prior to use.

Table 2.8 Drying Conditions for Several Polymers

Polymer	T_g [°C]	Equilibrium Moisture Content @ 100% RH [%]	Desired Moisture Content [%]	Maximum Drying Temperature [°C]	Drying Time [hr]
ABS	100	0.2 – 0.6	<0.02	80	2
Cellulose acetate	100	2.0 – 2.5	<0.05	90	1.5
Cellulose butyrate	100	1.0 – 1.5	<0.05	90	2
Nylon 6	50	1.0 – 3.0	<0.08	75	2
Nylon 66	50	1.0 – 2.8	<0.03	80	2
PMMA acrylic	100	0.6 – 1.0	<0.05	80	3
Poly-carbonate	150	0.15 – 0.3	<0.05	150	4

Polycarbonates are attacked by halogenated solvents, including common cleaning agents. This limitation is used to advantage when rotationally molded parts are to be solvent-assembled, painted, silk-screened, or otherwise decorated. Although PCs exhibit excellent weatherability, they tend to yellow after years of outdoor service, particularly if exposed to high temperature, either during the molding operation or during use. Fire-retardant, opaque grades are available. Although rotational molding grade FDA-approved PCs are available, the inherently low chemical resistance and high polymer cost limit FDA applications. As described in Chapter 7, polycarbonate does not experience as much shrinkage as crystalline polymers such as PE and nylon. As a result, draft angles must be increased to allow for ease of part removal. Stuck PC parts can be removed with an isopropyl alcohol spray, which stress-crazes the part into smaller pieces. Household ammonia will also stress-craze the stuck part.

2.7.2 *Cellulosics*

Cellulosics have been replaced by polyolefins and nylons for many commercial applications. Nevertheless, the cellulosics family, most notably cellulose acetate butyrate (CAB or CB) and cellulose acetate propionate (CAP or CP), should still be considered for transparent, highly colored applications

such as decorative globes. Cellulosics are considered crystalline with melting temperatures of 140°C to 190°C. However, the crystalline structure is not as well defined as with polyolefins. As a result, cellulosics can be processed at temperatures of about 180°C. Although cellulosics have lower heat resistance than polycarbonate or acrylics, they offer toughness at lower cost than polycarbonates and somewhat better impact resistance and solvent resistance than acrylics. Characteristically, cellulosics are hygroscopic although not to the same extent as nylons and polycarbonate. Nevertheless, care must be taken to maintain dry powder throughout the grinding, storage, and loading steps. Although CABs and CAPs can be pigmented for opacity, thermally stable dyes are normally used to maintain their transparency.

2.7.3 *Acrylics*

The most popular and technically important *acrylic* is *polymethyl methacrylate* (PMMA), which is traditionally given the following chemical notation:

$$-[CH_2-C(CH_3)(COOH_3)-]_x$$

PMMA is a moderately tough, transparent, highly weatherable amorphous polymer that finds substantial application in globes and shaped glazing. PMMA is attacked by halogenated chemicals. It can be easily solvent welded and painted. Acrylics do absorb moisture, but not to the extent of nylons and polycarbonates. Nevertheless, it is recommended that PMMA powder be kept dry from the grinding step through the molding step. Wet powder should be dried at 80°C and -40°C dewpoint for two hours prior to molding. Like PC, acrylic does not shrink as much as PE or nylon. As a result, provision must be made for part removal. PC-type draft angles, noted later, are recommended for PMMA.

2.7.4 *Styrenics*

The *styrenic* family includes *polystyrene, impact polystyrene, styrene-acrylonitrile* (SAN), and *acrylonitrile-butadiene-styrene* (ABS). The mer for polystyrene is:

$$(CH-CH_2-)_x-$$
$$\quad\;|$$
$$\quad\;\Phi$$

where Φ is the pendant phenyl group. Polystyrene (PS) is a brittle amorphous transparent plastic. Because of the phenyl group, PS is photochromic, meaning

that it is not suitable for outdoor application. Copolymers such as butadiene, a thermoplastic rubber, and acrylonitrile, a very tough, high-temperature amorphous polymer, are frequently reacted with PS to improve its impact resistance, albeit at the loss of transparency. ABS has excellent impact resistance and very good high temperature performance, although not nearly to the level of PC. Nevertheless, it is less expensive than PC and so is sought for structural applications including equipment housings of all types. ABS, with a protective surface layer of either acrylic paint or acrylic film, is used for exterior applications.

Rotational molding grades of ABS were commercial in the 1960s and 1970s.[58] Unfortunately, technologies to polymerize styrenics were dramatically modified and so ABS and other high-impact styrenics are rarely rotationally molded today.* The impact modifiers in current impact-resistant styrenics are badly oxidized and degraded by the rotational molding environmental conditions. Nevertheless, this limitation may be eased shortly by several developments. First, improved oxygen scavengers are under evaluation. Then, impact modifiers that are less oxygen sensitive show great promise. Also extensive process development is underway to use nitrogen as a purge or gas blanket throughout the rotational molding process, thus shielding the polymer from oxygen. Finally, methods of shortening the oven cycle time are now being evaluated.

2.8 Liquid Polymers

Liquid systems require a different technical approach than that of powder rotational molding. These liquid system technologies are described extensively below. First, it must be understood that there are many types of liquid systems, most of which are thermosetting resins. PVC plastisol and nylon 6 are the primary exceptions.

Thermosetting polymers usually begin as lower-molecular weight organics and therefore have lower viscosities. Molecular weight appreciation is achieved through the addition of a catalyst or similar reactive agent. Polymerization proceeds via reaction either at functional end-groups or by opening unsaturated double bonds along the backbone of one or more of the moieties. Polymerization of a polyfunctional thermoset results in the formation of a three-dimensional network, unlike the characteristic chain extension of difunctional urethane or amide.

* It has been estimated that the development of a thermally stable ABS of reasonable cost could signal an almost immediate 20% increase in the size of the U.S. rotational molding market.

Four major thermosetting families are *silicones, polyurethanes, epoxies,* and *unsaturated polyesters*. Traditionally, epoxies tend to have slow chemical reactions and relatively high-viscosity moieties and so have not found much interest in rotational molding.

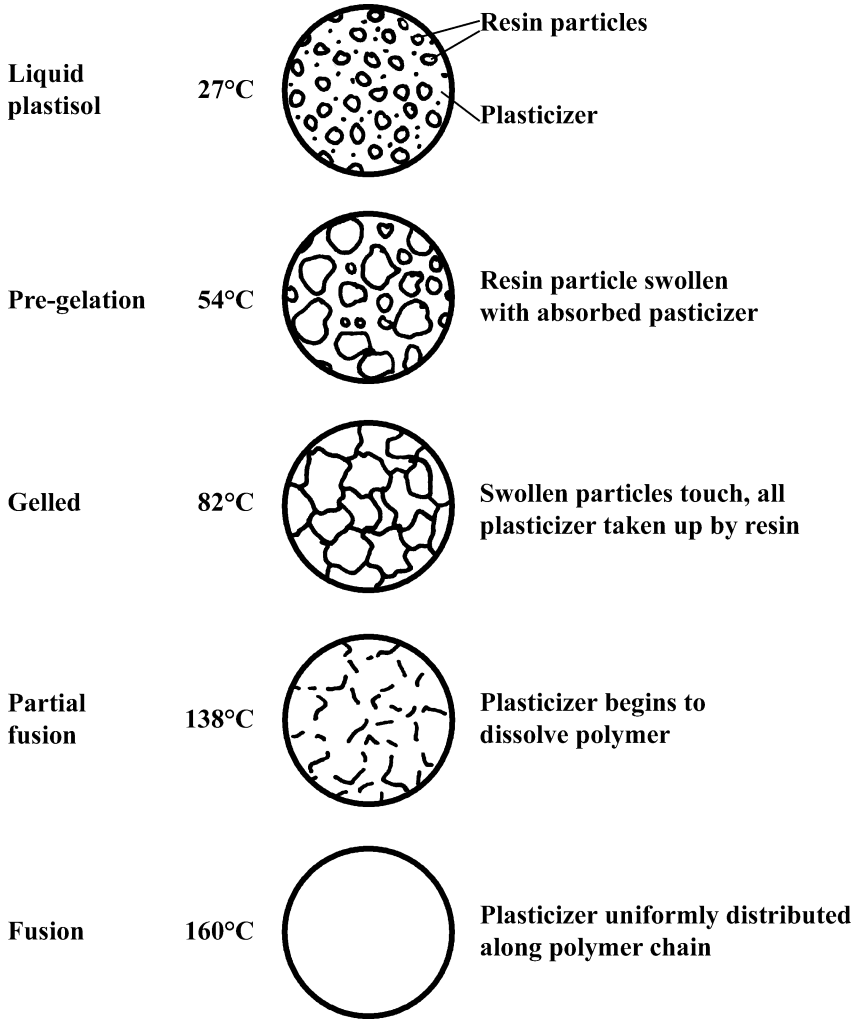

Figure 2.2 Effect of temperature on macromolecular characteristics of PVC plastisol, redrawn from Ref. 11

2.8.1 *PVC Plastisols*

Technically, PVCs are manufactured either by suspension polymerization or dispersion polymerization. Dispersion PVCs are characterized by 0.1 to 0.2 micron-sized particles. The liquid or paste plastisol is manufactured by suspending the dispersion resin in a plasticizer such as a phthalate, as shown in Figure 2.2.[11]

When the plastisol is heated, it passes through several characteristic changes. As the PVC approaches its glass transition temperature, the plasticizer begins to swell the PVC particles.[12,13] The plastisol is said to be gelled when the PVC has absorbed all the plasticizer, at a temperature about that of the PVC glass transition temperature. At this state, it is dry and crumbly, without cohesive strength. Fusion and the development of physical properties begins when the plastisol temperature reaches 120°C (280°F) or so. By the time the plastisol temperature is 190°C (380°F) or so, the plastisol is fully fused but still liquid. Fusion is technically defined as the condition where the microcrystallites of PVC have fully melted and the plasticizer is fully dispersed through the PVC. The torque rheometer is the traditional test for determining gelation and fusion conditions. A typical PVC plastisol isothermal

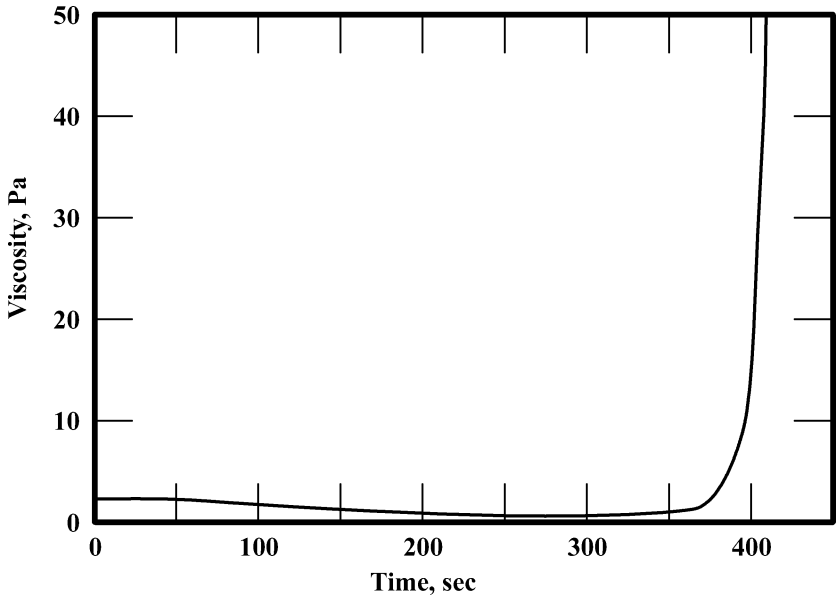

Figure 2.3 Typical time-dependent viscosity for PVC plastisol, redrawn from Ref. 14

time-dependent viscosity plot is shown in Figure 2.3.[14] Although technically PVC plastisol is not a reactive polymer, it undergoes characteristic changes that mimic reactivity. PVC plastisols usually produce very soft products, with Shore A Durometers down to 50 or so. They are used to produce doll heads, the ubiquitous beach balls, squeeze syringes, and interior parts for transportation vehicles.

2.8.2 *Polycaprolactam*

A single monomer, caprolactam as ε-amino caproic acid, $H_2N–(CH_2)_5–COOH$, polymerizes head-to-tail in the presence of heat and a catalyst, to produce $H_2N–[–(CH_2)_5–CO–NH–(CH_2)_5–]_n–COOH$, Nylon 6 also known as polycaprolactam. Viscosity increases as the molecular weight increases, as shown in Figure 2.4.[15] As noted below, properly catalyzed caprolactam is charged into a heated, isothermal mold prior to rotation. Nylon 6 has excellent chemical resistance to fuel oils, and so finds applications in fuel tanks and bladders. The chemistry of the catalyst-activated caprolactam reaction is detailed elsewhere.[16]

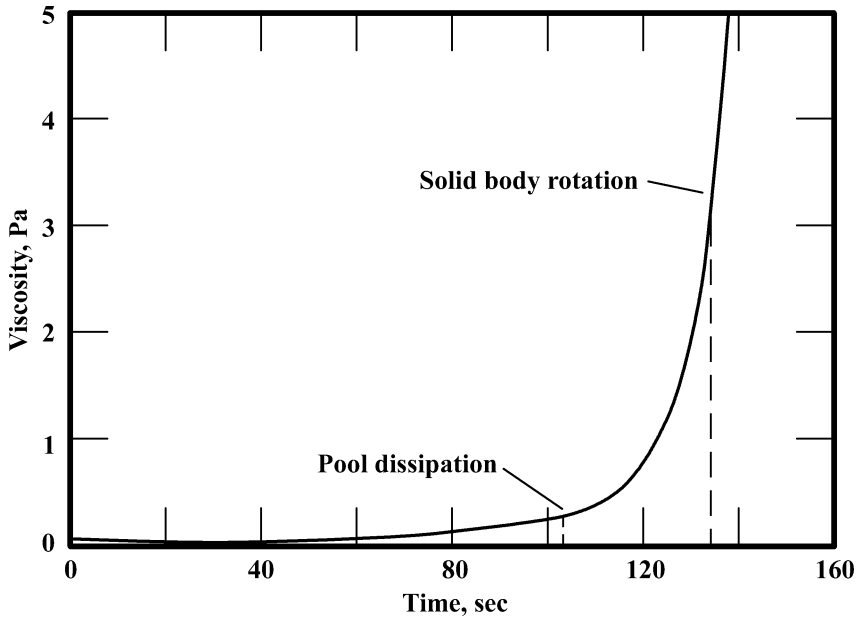

Figure 2.4 Time-dependent viscosity for reactive caprolactam (Nyrim), redrawn from Ref. 15 (Pool dissipation and solid body rotation described in Chapter 6)

The earliest effort to produce a rotationally moldable polycaprolactam was in 1959 by Allied Chemical Corporation.[17] In the early 1970s, the main application was as fuel tanks for the Ford Bronco, J.I. Case tractors, and U.S. Army electric generators. Generally half the caprolactam is mixed with a promoter and half with the catalyst. Since caprolactam is a solid at room temperature, it is necessary to heat the two components to 100°C (212°F) or so prior to mixing. The two very low viscosity streams are then high-shear mixed at this temperature and dispensed into the rotational mold. The mold temperature should also be maintained at at least 100°C (212°F). Currently DSM, The Netherlands, produces a recipe called Nyrim™, which yields a Nylon 6 block copolymer of alternating soft and hard segments. EMS-CHEMIE in Switzerland has developed a form of Nylon-12 called Grilamid Liquid Matrix System that is finding applications in the rotational molding of high performance fiber reinforced parts.

As the polycaprolactam is formed, the resin viscosity rises, slowly at first, then very rapidly to a gel state. As polymerization continues, crystallization begins. As expected, crystallization level increases with increasing oven time. However, as the reaction continues, the rate of crystallization slows dramatically, increasing from just under 34% after 2.5 minutes to around 35% after 10 minutes (see Figure 2.5[18]). Even at the very beginning of development

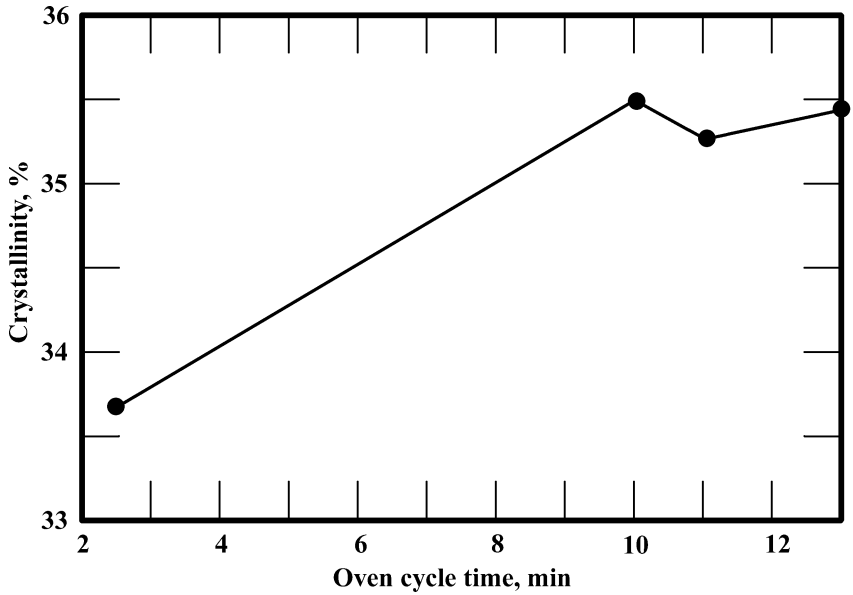

Figure 2.5. Effect of oven time on crystallization level of polycaprolactam (Nyrim), redrawn from Ref. 18

work on caprolactam, it was recommended that a multilayer technique be used, where successively, thin layers of caprolactam coat the mold wall, react, gel, and crystallize before the next charge is added. Since the freshly reacted caprolactam has a very low viscosity at 100°C (212°F), fillers such as milled glass and hollow glass spheres have been used to "bulk up" the resin. Recent studies find that at loadings up to 7% (wt), fillers do not appreciably alter the zero-shear viscosity of the caprolactam but do reduce the rate at which the viscosity accelerates to the gel state.[19]

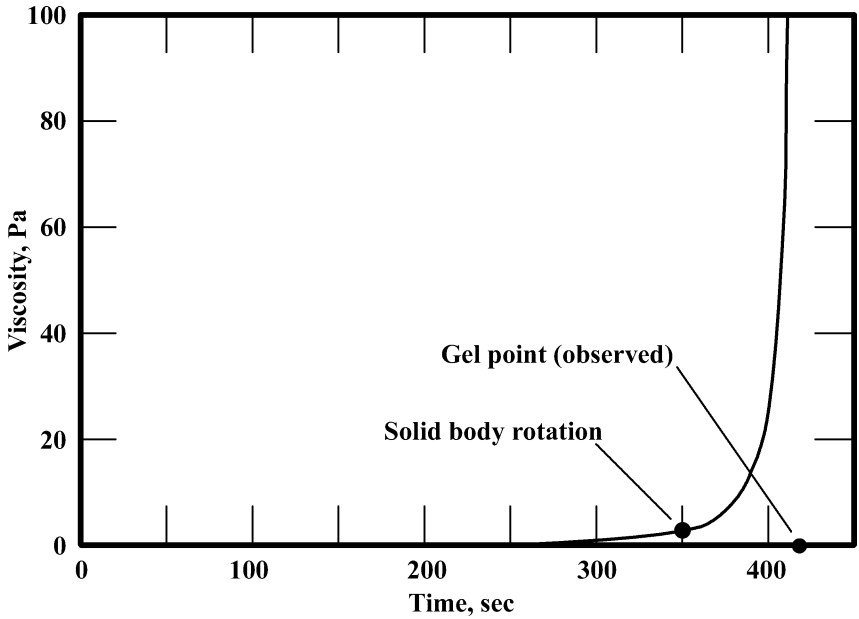

Figure 2.6 Time-dependent viscosity for rigid polyurethane, redrawn from Ref. 20 (Solid body rotation discussed in Chapter 6)

2.8.3 *Polyurethane*

There are two types of thermosetting resins, those that exothermically heat and gel or form intractable structures at about the same time and those that gel long before the heat of reaction is measurable. Polyurethanes generate heat very quickly. Unsaturated polyester resins do not. Polyurethane (PU or PUR) is created by the reaction of an isocyanate, HO–R–OH, and a polyol, O=C=N–R'–N=C=O, to produce $(–O–R–O–CO=NH–R'–NH–CO–)_n$. A common polyurethane is equal parts of toluene diisocyanate (TDI) and diethylene glycol. Another uses diphenylmethane-4,4'-diisocyanate (MDI) and a

mixture of di- and triethylene glycols. When the polyurethane recipe is catalyzed, it is charged into an unheated mold. The exothermic reactive energy quickly increases temperatures of the mold and liquid resin. Typically, no additional heat is needed to sustain the reaction. Polyurethanes are usually automatically mixed, dispensed, and metered. Time- and temperature-dependent viscosities for a typical rotationally moldable polyurethane are shown in Figure 2.6.[20]

2.8.4 *Unsaturated Polyester Resin*

Unsaturated polyester resin (UPE)* was one of the earliest liquid polymers to be rotationally molded.[22] ** Like PVC, polyester is a 19th century polymer. In 1847, Berzelius reacted tartaric acid with glycerol to produce a sticky resin. Lorenzo reacted ethylene glycol with succinic acid in 1863 to produce a second polyester. Today, polyester is prepared by reacting diethylene glycol, HO–CH_2–CH_2–OH, and an unsaturated aliphatic acid such as maleic acid, HOOC–CH=CH–COOH. The still-unsaturated polyester resin is then dissolved in an unsaturated, reactive solvent such as styrene or α-methyl styrene. The resin viscosity is adjusted by the extent of polymerization of the polyester, the nature of the ingredients used to produce the polyester, and by the amount of reactive solvent. The resin is crosslinked by adding a free-radical catalyst such as methyl ethyl ketone peroxide (MEKP). Polyester resin reactions are typically very slow, with gelation taking many minutes. The reaction exotherm is developed mainly after the polyester resin has gelled into an intractable structure. Polyester resins have great affinity for fillers and reinforcements, with filler loading as high as 70% (wt) possible. Fillers include calcium carbonate and talc inorganics and wood flour organics. Reinforcements include cotton lintels and fiberglass. Furthermore, polyester resins can be painted and stained, and have excellent weather resistance. As a result, thermosetting polyester resins have found extensive use in furniture and construction. In rotational molding, the polyester resins must be heated to initiate reaction in reasonable times. As discussed below, care must be taken to ensure that the resin fully coats the mold surface prior to gelation. Otherwise the gelling resin remaining in the pool will wipe the resin from the mold surface. The difficulty in balancing the heating and reaction aspects of rotationally molding catalyzed unsaturated polyester resin has limited its applications despite its exceptional price/performance ratio.

* Ref. 21 is an excellent but dated reference, available now only in technical libraries.

** Rotationally molded pecan-filled polyester resin lamp bases were sold commercially in the late 1950s.

2.8.5 *Silicones*

Silicones are also slowly reacting but initial viscosities can be adjusted by proper selection of molecular weight. The general composition is based on polydimethylsiloxane:

$$\begin{array}{c} CH_3 \\ | \\ RO - (Si - O)_x - R \\ | \\ CH_3 \end{array}$$

For room-temperature cured silicone elastomers, x is on the order of 200 to 1000. For heat-cured silicones, x is on the order of 3,000 to 10,000. Room-temperature vulcanizing (RTV) silicones are either reacted with atmospheric moisture or with separate tin salt catalysts. Heat-cured silicones may not require a catalyst but an accelerant is usually included in the recipe to allow full vulcanization in a reasonable cycle time. Silicone elastomers are desired for their very high solvent resistance and their performance over very wide temperature ranges, from about 300°C to -100°C, with lifetimes of 5 to 10 years or more.

Thermosets have always intrigued rotational molders. Since the reactions are exothermic, only a modicum of heating energy is needed to initiate the reaction. As the final shape is created by reaction, very little cooling is required. Consequently, the rotational molding equipment needed for reactive thermosetting liquids can be quite rudimentary when compared with equipment for polyolefins, say. The minimization of energy costs and water recycling more than offset the higher materials costs for polyurethanes and UPEs. However, the primary processing problem lies in the fluid mechanical effects that are manifested during the rotating process.*

2.9 In-Coming Material Evaluation

In-coming material evaluation is also important if effective quality control is to be maintained. In general, polymer suppliers "certify" or legally guarantee the performance of their materials. Melt viscosity (melt index) and powder particle characterization are two tests that should be run periodically by the rotational molder. Melt index should also be run on sections

* These problems are detailed in Chapter 6.

from molded parts, to make certain that the polymer has not degraded in the molding process.

There are many ways of determining polymer material characteristics, including chemical analysis, infrared analysis, differential scanning calorimetry, and thermomechanical analysis. These tests are detailed elsewhere[23–25] and are not of prime interest to the rotational molder. Polymer melt index and powder properties are important.

2.9.1 *Melt Index and Melt Flow Index*

For most polymers, increasing molecular weight means increasing melt viscosity. And for most polymers, increasing molecular weight means improved properties such as impact strength and toughness. In the 1950s, a rapid laboratory test for relating polyethylene molecular weight to melt viscosity[26] was developed. The "extrusion plastometer" test has evolved into ASTM D-1238.[27] As shown in Figure 2.7,[28] the extrusion plastometer is a heated, jacketed, vertical cylinder, open at the top and plugged at the bottom with a calibrated die. Polymer is placed in the tube [B], and a solid piston is then placed in the tube, against the polymer. The polymer is heated to a specific temperature, such as 190°C for polyethylene or 230°C for PP. A fixed weight [A], is then placed on the piston top. The weight forces the polymer through the calibrated die. Polymer is collected in a predetermined period of time, such as 10 minutes. The weight of the polymer, in gm/10 min or decigram/min, along with the melt temperature and the applied weight or stress, is then reported as the melt index or MI of the polymer. Sometimes PP values are reported as MFI (melt flow index) values.

Although the melt index procedure was devised specifically for polyethylenes and extended somewhat hesitantly to PPs, the ASTM test now includes extensive conditions for other rotationally moldable polymers. Table 2.9 from the ASTM test gives recommended temperatures and applied stresses for many polymers. Note in many cases, more than one set of conditions are given for a specific polymer. Table 2.10 gives recommended timing intervals for polymers with various melt indexes.

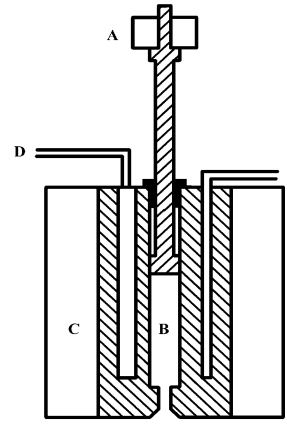

Figure 2.7 Classic melt indexer, redrawn from Ref. 28, with permission of Hanser Verlag, Munich (A, Static weight; B, Tube with Polymer pellets, melt; C, Insulation; D, Heating medium)

Table 2.9 Melt Index Test Conditions for Various Polymers

Polymer	Temperature, °C	Applied Stress, kPa	Applied Stress, lb/in^2
LMWPE	125	44.8	6.5
LMWPE	125	298	43.3
Polyvinyl acetate	190	44.8	6.5
LDPE, Cellulose ester	190	298	43.3
LDPE, Cellulose ester	190	2982	432
PS, ABS	200	689	100
Acrylic, PS	230	165	24
Acrylic, PS	230	524	76
FEP	265	1724	250
Nylon, PA-66	275	44.8	6.5
Polypropylene	230	298	43.3
HDPE	190	1379	200
Polycarbonate	300	165	24
HIPS	190	690	100
Nylon, PA-6	235	138	20
Nylon, PA-6	235	298	43.3
Nylon, PA-6	235	690	100
PET	250	298	43.3

Table 2.10 Time Interval for Various Melt Index Polymers

MI, g/10 min	Testing Time, min
0.15 to 1.0	6.00
1.0 to 3.5	3.00
3.5 to 10	1.00
10 to 25	0.50
25 to 50	0.25

2.9.2 *Sieving*

In Chapter 3, ways in which polymers are ground to rotational molding grade particle sizes are considered. Various ways of characterizing particle sizes are presented, and some discussion on powder density is also given. Even though there are many ways of determining particle size distribution of rotational molding grade powders, sieving is still the most common method. The typical screen size distribution is -35 mesh to +200 mesh, although -35 mesh to +150 mesh is sometimes requested. The ASTM E-11 U.S. Sieve Sizes are given in Chapter 3. Typically, powders are pulverized from resin supplier-supplied extruded pellets. High densification is achieved by a relatively broad particle size distribution. Recently, micropellets of nominal 1500-micron dimension are being produced by direct extrusion.

ASTM D-1921[29] describes the traditional dry sieving method. Recommended shaking time is 10 minutes at the rate of about 150 taps per minute. After shaking, the powder retained on each sieve is weighed. If the cumulative weight is less than 98 percent of the initial weight, the test must be repeated. Bulk density and pourability of the incoming powder are determined according to ASTM D-1895.[30] The bulk density is obtained by filling a cylinder of a given volume with plastic powder, then weighing the powder. Pourability is "… a measure of the time required for a standard quantity of material to flow through a funnel of specified dimensions." A 20-degree angle funnel, stopped at its small end, is filled with a weighed amount of powder. The stopper is removed and the time it takes for the powder to flow from the funnel is measured. Association of Rotational Molders (ARM) recommends this test, as a way of determining the flowability of powder inside the mold cavity.

2.10 Product Testing Protocols and Relationship to Polymer Characteristics

Product testing is important in rotational molding. Undercured* parts lack mechanical strength. Overcured parts may be chemically degraded. Two levels of product testing are described here. In certain instances, the entire product may need to be tested, particularly if combinations of environmental factors are critical. An example is a chemical fertilizer tank that is subjected to chemical attack, long-term weathering, and mechanical vibration. Tests on sections of parts tend to be more controlled and easier and less costly to perform. Many standard tests have been developed for determining polymer properties on specimens cut from molded products.**

2.10.1 *Actual Part Testing — Protocol*

There are several reasons for testing,[31] including:

- As a basis for quality control
- To provide methods of comparing and selecting materials
- To establish a design database, to predict service performance
- To focus materials development
- To provide methods for obtaining polymeric materials behavior under load

There are two general classes of test specimens: *full-scale* tests on finished parts and *focused* tests on sections or *segments* taken from the parts. Table 2.11 lists advantages and disadvantages for each of these testing protocols.

Table 2.11 Testing Protocols

Full-Scale Tests — Advantages
• Results relate directly to final part performance
• Extrapolation of data unneeded
• Combined tests possible, such as long-term UV and drop impact, or chemical resistance under load
• "Seeing is believing" important for sales and litigation

* Although the term "cure" is used most often for thermosets, the term has become traditional in the rotational industry. "Cure" indicates the extent to which the thermoplastic powder particles have become melted and coalesced.

** Chapter 7 gives technical details on short-, normal-, and long-term testing of rotationally molded parts.

Full-Scale Tests — Disadvantages

- Parts may be too large for all but simple mechanical tests such as drop tests
- Testing may destroy several parts that otherwise could have been sold
- Test data may not relate back to standard polymer properties such as modulus or impact strength
- Instrumentation may be difficult and/or expensive
- Testing may be expensive and time-consuming

Segment Tests — Advantages

- Testing is done in controlled environment
- Many segments may be taken from a given part
- Test data should relate to standard polymer properties*

Segment Tests — Disadvantages

- May be difficult to correlate laboratory tests to actual part performance, particularly in short-term testing such as drop testing and long-term testing such as chemical resistance and creep
- Removal of segments from part may act to relieve stresses or affect crystallinity in segment, thereby biasing the data
- Laboratory testing may be time-consuming, expensive, and may be irrelevant to actual part performance

The person responsible for determining whether the product will pass the original design criteria must consider two general aspects of testing protocol. First, he/she must apply two criteria of test acceptability to every test:

- The mechanical state should be definable in physical terms such as thickness, length, applied load, applied stress, strain, rate-of-strain, dimensional change, and temperature
- The mechanical state should be definable in causal mathematical terms, such as stress-strain-rate-of-strain or WLF equation.

These criteria are rarely met when testing actual parts. Usually a compromise must be struck between generating fundamental information, evaluating, in a realistic way, the behavior of the molded part, and economics. It is always prudent to determine the cost involved in the testing program. Although a comprehensive discussion of the interrelationship between product performance and the cost of testing is beyond this treatise,** certain cost

* See comments on testing criteria below.

** See Shrastri.[32] The paper summarizes the work of the International Technical and Standards Advisory Committee of The Society of the Plastics Industry, Inc. (ITSAC/SPI) and involved seven testing facilities in the U.S., U.K., and Germany.

estimates in Table 2.12 emphasize the importance of ensuring that the test data are relevant.

Table 2.12 1998 Cost of Material Data Generation[32]

Properties	Cost Estimate per Grade	First Guess
Single-Point Data		
Mechanical properties	$ 780 – $3120	$1500
Thermal properties	$1030 – $3270	$1500
Rheological properties	$ 370 – $ 650	$ 500
Electrical properties	$1020 – $1860	$1500
Other properties	$ 170 – $ 540	$ 250
Multiple-Point Data (such as tensile creep to 10,000 hr)	$14,484 – $93,140	$25,000

These are costs from laboratory testing in controlled environments on prepared test specimens. Costs involved in strain-gauge instrumenting a product such as an agricultural tank that is subsequently filled with liquid and dropped or buried with rip-rap backfill may be substantially higher than the values given in this table.

2.10.2 *Actual Part Testing — Entire Parts*

There is nothing more spectacular than a thousand-gallon rotationally molded XLPE tank half filled with water being dropped from a crane several feet to a concrete floor. A steel weight swung into a nylon tank containing fuel oil will always draw a crowd. A little less impressive is an agricultural grain silo swaying under 100 mph wind gusts in a wind tunnel. Less spectacular but equally impressive is a 1000-hour test of a rotationally molded polyoxymethylene (acetal or POM) vat containing Igepal-laced boiling water.* These tests and myriad others represent a class of practical, full-scale, or "true to life" product tests. These tests are typically categorized as drop or impact tests, environmental or chemical resistance tests, and long-term creep or fatigue tests.

Full-scale tests should always follow batteries of prescreening tests on polymers and postmolding tests on sections removed from the molded parts. Full-scale tests should serve several purposes. They should confirm the proper

* Igepal is a cracking agent that simulates the active environmental stress cracking agent in detergents. Igepal is added at 1% (wt), 5% (wt), or 10% (wt) to water, depending on the severity of the test. ESCR or environmental stress crack resistance testing is described further in this chapter.

selection of the polymer and the predicted effect the process has on the polymer properties. They should also confirm that the original design criteria had sufficient inherent safety factors. They provide visual support that the product will survive anticipated field use and abuse. And they act as spectacular visual props for marketing and prospective purchasers.

Full-scale tests sometimes point up inadequacies in laboratory or controlled environment tests. For example, laboratory tests might indicate that the polymer of choice is resistant to the chemical to be stored in the product and that, in separate tests, it resists designed impacts. However, full-scale tests might show that the product fails when dropped after having been filled with the chemical for several months. Figure 2.8 shows the time-dependent failure stress at 60°C for several 918 kg/m^3 LDPEs.[33]

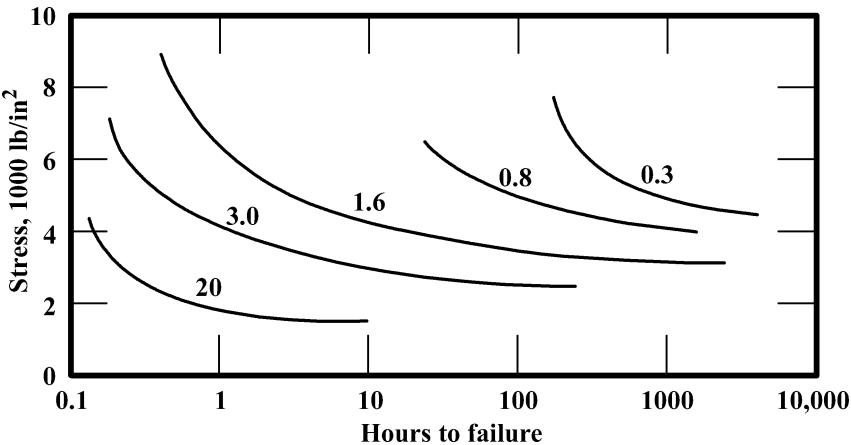

Figure 2.8 ESC failure of 918 kg/m^3 LDPE at 60°C in 10% Igepal, showing effect of Melt Index [MI], redrawn from Ref. 33, with permission of Hanser Verlag, Munich

2.10.3 *Actual Part Testing — Sections*

It is not always physically practical, economically feasible, or technically accurate to test entire molded parts. Controlled laboratory testing usually begins with test specimens that are very carefully cut from the molded part. Several important classes of tests are described here.

2.10.3.1 *Molded Part Density*

The polymer densifies during the rotational molding process. The final part properties in many respects are strongly dependent on final part density. For polyethylene, for example, there is a strong relationship between density and impact strength. The density gradient column is a standard way of determining part density. ASTM D-1505 details the construction of a standard density gradient column. The liquid system for polyethylene and polypropylene is isopropanol and water. Several glass floats of different densities, usually obtained from a scientific supply house, are required. Ideally the floats should be of different colors for easy identification. Two aspects of the test must be carefully followed. First, the specimens must be free of all surface bubbles. Then the specimens must be wetted with isopropanol prior to insertion into the column. Equilibrium is reached in several minutes to an hour.

The calibration of the columns should be checked regularly and those that show drifting of the density gradient should be discarded and remade. It is also unwise to allow the column to become cluttered with too many test samples. These should be cleared regularly from the column using a coarse-screen scoop that is slowly raised through the column. Columns more than a week old or containing more than 20 samples or so should be discarded and remade.

2.10.3.2 *Drop Tests*

Many rotationally molded parts are subjected to either whole part impacting or localized impacting. Whole part drop impacting was discussed earlier. Road stones might locally impact vehicle fuel tanks. Trash containers might be impacted by debris during filling. Most polymers fail under impact in characteristic fashions. Four general failure modes are encountered:[34]

- *Ductile failure*, where the polymer yields prior to failing. Epoxy-modified PVC and PC are plastics that typically exhibit ductile failure.
- *Ductile yielding*, where the plastic deforms locally and may stress whiten, but does not crack or break. Polyolefins are typical ductile-yielding polymers.
- *Localized cracking* without breaking into discrete pieces or losing shape or integrity. Localized crazing or stress-whitening may accompany the cracking. Certain grades of nylon exhibit localized cracking.
- *Brittle fracture*, where the plastic breaks into discrete pieces and/or the impact area is punched from the rest of the part. PS and PMMA are typical brittle fracture polymers.

The demarcation between these failure modes is quite indistinct. As a result, most plastics are classified as exhibiting either ductile fracture, where the polymer yields before failing, or brittle fracture, where the polymer exhibits no yielding before failing.[35] * Ductile-brittle transition is temperature-dependent, as seen in Figure 2.9 for PMMA.[36] The brittle temperatures for several polymers are given in Table 2.13.

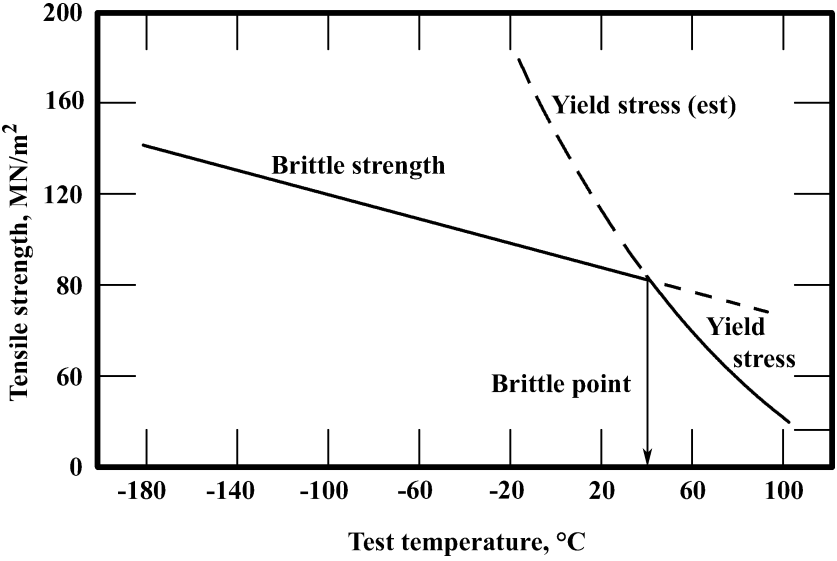

Figure 2.9 Ductile-brittle transition temperature for PMMA, redrawn from Ref. 36, with permission of John Wiley & Sons, London

Table 2.13 Approximate Brittle Temperatures for Various Polymers Adapted from[37] (Actual temperature depends on polymer adduct package, rate of impact)

Polymer	Brittle Temperature, °C
PC	145
Polystyrene	100
PMMA	80
PP homopolymer	10
RPVC	-50**
LDPE	-65
HDPE	-90

* Association of Rotational Molding 1986 guidelines for low-temperature impact testing list only two failure definitions — ductile and brittle.

** Strongly dependent on nature of impact. Could be as high as +60ºC in certain circumstances.

The following factors influence the impact resistance of a polymer and the product made from its plastic:

- Degree of crystallinity
- Extent of notches
- Method of loading
- Molecular orientation
- Molecular weight, molecular weight distribution
- Polymer notch sensitivity
- Processing conditions
- Rate of impact
- Residual stress field
- Temperature

There are four types of impact tests in use today:[38]

- Pendulum or swinging weight impact against a fixed bar-type sample
- Falling weight to fracture against a disk sample
- Constant velocity puncture of disk or section of product
- Tensile impact

The first two are usually used in rotational molding. ASTM D-256 details the pendulum or swinging weight test. If the sample is a rectangular beam held vertically fixed on one end, the test is a cantilever impact or Izod test. If the rectangular beam sample is held horizontally fixed on two ends, the test is a supported beam impact or Charpy test. The specimen may be notched or unnotched. Notching is recommended if the polymer is notch-sensitive, such as polycarbonate, or if the product contains sharp internal radii that may be subjected to impact loading. ASTM D-3029 details the falling weight to impact test, sometimes characterized as the flexed-plate impact test. An older version of this test uses an inert tup or weight that is dropped at increasing heights until failure is achieved. Newer versions of this test use a tup that contains deceleration and energy absorption electronics.

Two testing methods are used. The *Probit method* uses many test specimens and a random pattern of drop heights. The impact energy to break is the drop height value where 50% of the samples fail. The *Bruceton method* also uses many test specimens, but the drop height is determined by first picking an arbitrary drop height, then decreasing the drop height if the first sample fails or increasing it if it doesn't. The Bruceton method is sometimes called

the staircase method or the "up-and-down" method.* The impact energy to break is the drop height where the sample just fails. The Association of Rotational Molders standard impact test uses the falling weight Bruceton method.

2.10.3.3 *ASTM Tests for Mechanical Properties***

Handbooks on testing list dozens of standard procedures for determining polymer mechanical performance.[23] Procedures are usually categorized in terms of the time span of the event. Impact and the primary event of vibration are short-time events. Creep, stress relaxation, and fatigue failure are long-time events. Tensile and flexural loading are usually considered moderate-time events.

Flexural and Tensile Moduli. Modulus is the slope of the polymer stress-strain curve. For plastics, it is temperature dependent. Five moduli may be given in polymer data sheets — flexural modulus, tensile modulus, compressive modulus, secant modulus, and shear modulus. The first two are important in rotational molding. ASTM D-790[39] is the standard test for determining polymer flexural modulus. It is a three-point bending test using a beam that is rectangular in cross-section. The rate at which the beam is bent (the strain rate) must be sufficiently fast to ensure that the polymer is reacting entirely elastically to the applied load. As the load is applied, the surface of the beam further from the load is under tension and the surface closer to the load is under compression. The neutral axis, or the plane where the beam is neither under tension nor compression, must remain within the beam during the test.

ASTM D-638 is the standard test for determining the tensile modulus of a polymer. The specimen is usually dogbone in shape, with the testing area being a beam that has a rectangular cross-section. The wider sections of the specimen are gripped in the machine vises. Again, the rate of load application must be sufficiently fast to ensure that the polymer is behaving elastically. The tensile test is also used to determine yielding point, if any, and elongation at break. Along with the modulus data, the strain rates for both these tests should be reported as *percent strain per unit time* or %/*min*.

Creep. Creep under load is the bane of many plastic parts. In many cases, plastic parts are required to sustain static applied loads for extended periods

* In 1986, The Association of Rotational Molders approved a low-temperature impact test that follows the ASTM D-3029 method and recommended the Bruceton Method for determining the energy to impact at -40°C temperature.

** The reader is referred to Chapter 7 for mechanical performance of rotationally molded polymers under various loads.

of time. Unlike metals and ceramics, plastics deform continuously under applied load, even at moderately low temperatures (close to room temperature). The result is permanent distortion, even when the load is removed. ASTM D-2990 is a uniaxial tensile creep standard, whereby a polymer specimen is hung vertically with a weight attached to the lower end. The time-dependent stretching of the specimen is called *creep*. If the specimen fails under the load, the mode of failure is called *creep rupture*. The rate of stretching is dependent on the load value. Creep and creep rupture are highly temperature-dependent. As with impact, certain polymers such as PMMA fail in a brittle manner, while others such as polyethylene exhibit ductile failure. There has been some success in characterizing polymer creep performance in terms of a time-dependent flexural modulus,[*,**] such as:

$$E(t) = E_0 f(t) \tag{2.1}$$

One curve-fitted model is:

$$E(t) = E_0 e^{-at} \tag{2.2}$$

Flexural Fatigue. The failure of a polymer under repeated fluctuations in load (or deformation) is called *fatigue*. ASTM D-671 is a standard for determining the polymer response to applied flexural bending. The sample is a very carefully shaped specimen, designed to provide uniformly increasing bending moment from the grip end to the flexing end. There are severe restrictions to the direct application of the data.[***] As a result, if a given rotationally molded part will experience periodic loading during use, it is strongly recommended that the part itself be thoroughly tested under expected loading conditions.

2.10.3.4 *Color*

Color is the most subjective and opinionated area of materials technology. Some of the factors that influence the color of plastics are:

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[*] Many sources call this the "creep modulus."

[**] Correctly, the stress applied to the specimen, σ, is constant, but the specimen elongates as a function of time, or its strain increases with time, $\varepsilon(t)$. Modulus is the ratio of applied stress to stain, $E(t) = \sigma/\varepsilon(t)$. Since $\varepsilon(t)$ increases with time, $E(t)$ must therefore decrease with time.

[***] According to the standard, "The results are suitable for direct application to design only when all design factors including magnitude and mode of stress, size and shape of part, ambient and part temperature, heat transfer conditions, cyclic frequency, and environmental conditions are comparable to the test conditions."

- Color intensity
- Environmental light source wavelength dependency
- Gloss
- Level of crystallinity
- Thickness

Some of the rotational molding processing factors that influence the color of plastics include:

- Processing temperature
- Time at processing temperature
- Rate of cooling relative to rate of crystallization

An international standard, the CIE standard,* has been established and computerized to mitigate disagreements regarding colors. The DIN 5033 X,Y,Z orthogonal coordinate chromaticity diagram has largely been replaced with the CIELAB L^*,a^*,b^* orthogonal coordinate method.[40] Relatively inexpensive laboratory colorimeters that yield L^*,a^*,b^* values to within 1% accuracy are now available. The rather complicated conversion between X,Y,Z and L^*,a^*,b^* coordinates is usually part of the colorimetry software. Hand-held colorimeters with 5% accuracy are also available for use on the production floor.

2.10.3.5 *Chemical Tests*

Rotationally molded plastic parts must usually be resistant to chemical attack. Generally, there are several levels of chemical attack.[41] Many plastics are degraded or chemically altered by direct chemical reaction with the environment. Polyethylene, for example, crosslinks in the presence of high-temperature oxygen. In rotational molding, this occurs on the inside of the molding, and results in oxygen-driven crosslinking and yellowing.

Plasticization is the absorption of small chemically benign molecules that migrate between the macromolecular chains, thus allowing the plastic part to lose stiffness. Water is a plasticizer for nylons. Benign plasticizers usually migrate readily into and out of the part, depending on simple concentration gradient driving forces. Solvation is the absorption of a chemically aggressive molecule that swells or even dissolves the polymer. Ketones solvate styrenics. Aggressive solvents can also migrate, albeit quite slowly, but while absorbed in the polymer, frequently imbrittle or

* The Commission Internationale de l'Eclairage standard, DIN 6174.

degrade it. Time-dependent haze formation in a plastic part may be the result of solvation. Crazing is the time-dependent formation of microcracks in the surface of a plastic part, again due to solvation. Absorption, plasticization, and solvation can occur in a stress-free part. Stress-cracking is the time-dependent failure of a plastic part under stress. Note that the stress can be either inherent, due to the molding conditions, or induced as the product is being used.

2.10.3.6 *Environmental Stress Crack Test*

Two tests are used to determine polymer resistance to chemical attack. The older is the bent strip test, where a carefully dimensioned polymer strip is clamped against an elliptical shape (see Figure 2.10[42]). The assembly is immersed in a cracking agent solution at a predetermined temperature. After one minute, the sample is examined for stress cracking. If none is seen, the sample is reimmersed for extended periods of time, up to

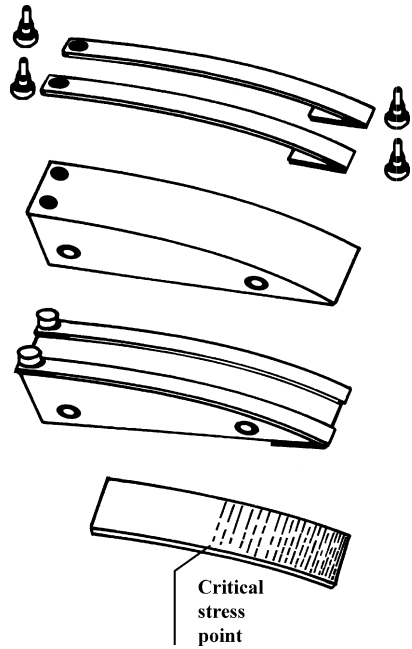

Figure 2.10. Environmental stress crack resistance or ESCR bent strip test, redrawn from Ref. 42, with permission of John Wiley & Sons, New York

1000 hours. Since the strip is bent elliptically, the level of stress changes nearly linearly from one end to the other. The critical stress point is the point where stress cracking is no longer apparent. Of course, this point is usually a strong function of temperature, time, cracking agent concentration, and the nature of the cracking agent. ASTM D-1693 uses a series of notched specimens that are bent through 180 degrees. The standard calls out a specific type of notching jig to be used, specific dimensions for the sample and the notch, and specific designs for the specimen holder and test assembly. The cracking agent in this test is 10% (wt) Igepal C0-630 and the test assembly is to be immersed in a constant temperature bath at either 50°C or 100°C.

It is well-documented that polyethylene ESCR is improved by increasing molecular weight, reducing stresses, and including elastomers in the polymer recipe. Morphologically, smaller spherulites, narrower molecular weight distribution, and lower molecular orientation all improve ESCR.

Recently, a constant stress test has been developed to quantify the stress crack resistance of rotational molding grade of polyethylene.[57] This is a difficult and costly test to perform but it is felt that it gives a more realistic representation of the performance of a molded part in service. Until the test data become more widely available, it is likely that results from both types of tests will be used to evaluate material performance.

2.10.3.7 *Chemical Crosslinking and the Refluxing Hexane Test*

Certain polymers such as polyethylene benefit by being crosslinked. Resistance to creep, compression set, and stress relaxation is improved. Thermal expansion coefficient is reduced. Heat distortion temperature, glass transition temperature, and tensile strength increase. The greatest drawback to crosslinking is the inability to regrind and reprocess the polymer. Since trim and flash from rotational molding is very low, the lack of reprocessability is not considered a serious penalty. Organic peroxides are the common crosslinking agents for polyethylene. These are compounded into the polymer prior to grinding. Table 2.14 gives typical peroxide-based crosslinking agents for polyolefins:

Table 2.14 Organic Peroxide Crosslinking Agents Adapted from Ref. 43

Chemical Name	Decomposition Temperature, °C		Maximum Compounding Temperature, °C
	1-min half-life	10-hr half-life	
1,1-Di-tert-butyl Peroxy-3,3,5-trimethyl cyclohexane	148	95	100
Dicumyl peroxide	171	115	120
2,5-Dimethyl-2,5-di(tert-butyl peroxy) hexane	179	119	130
tert-Butyl-cumyl peroxide	178	119	130
α,α′-Di(butyl peroxy)-diisopropyl benzene	182	122	125
Di-tert-butyl peroxide	—	125	130
2,5-Dimethyl-2,5-di(tert-butyl peroxy) hexyne	193	128	140
1,10-Decane-bis(sulfonyl hydrazide)	194(?)	140(?)	145

It was noted above that ASTM D-2765 is the standard test for determination of the extent of crosslinking in a rotationally molded polyethylene part.[44] In short, a weighed sample of the polymer is placed in a 120-mesh stainless steel wire cage that is suspended in a refluxing flask. Solvent, either decahydronaphthanate or xylene, is added to cover the cage and sample. The sample is held in boiling refluxing solvent for 6 hr for decahydronaphthanate or 12 hr for xylene. The sample is then removed and dried in a 28 mm Hg vacuum dryer at 150°C for up to 2 hr, then reweighed. The extent of crosslinking is the ratio of weights, before and after.* It is well known that significant changes in the characteristics of polyethylene are achieved only when gel content exceeds about 50%,[45] and for rotational molding, gel content of 70% to 80% is recommended. Figure 2.11 shows the level of crosslinking as percent gel as a function of the dosage level of 2,5-dimethyl-2,5-di(tert-butyl peroxy) hexyne. Long-time stability is achieved with dosages in excess of about 0.3% (wt).[46] Figure 2.12 shows stability in percent gel in terms of time and concentration of 2,5-dimethyl-2,5-di(tert-butyl peroxy) hexyne in 0.7 MI HDPE.[47]

* Note that to achieve an accurate gel fraction, the weights of inorganics such as fillers and pigments used with the polyethylene must be subtracted from the before and after weights.

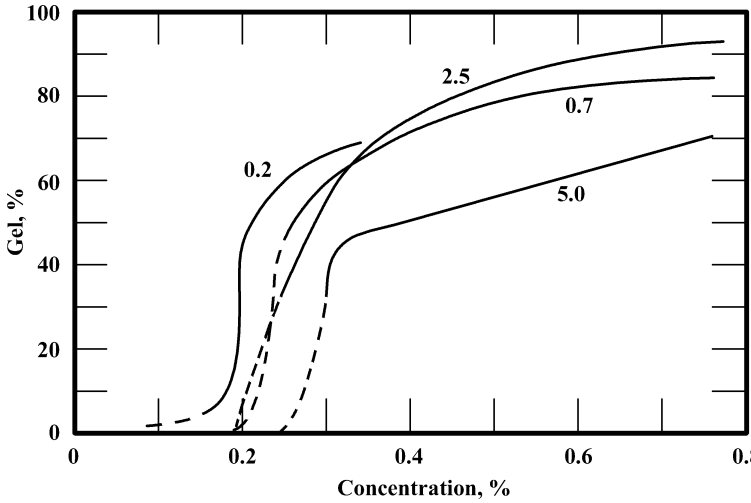

Figure 2.11 Effect of peroxide crosslinking agent concentration [wt %] on gel percentage of HDPE for various melt indexes [MI], redrawn from Ref. 46, with permission of John Wiley & Sons, New York. Crosslinking agent is 2,5-Dimethyl-2,5-di(tert-butylperoxy)hexyne

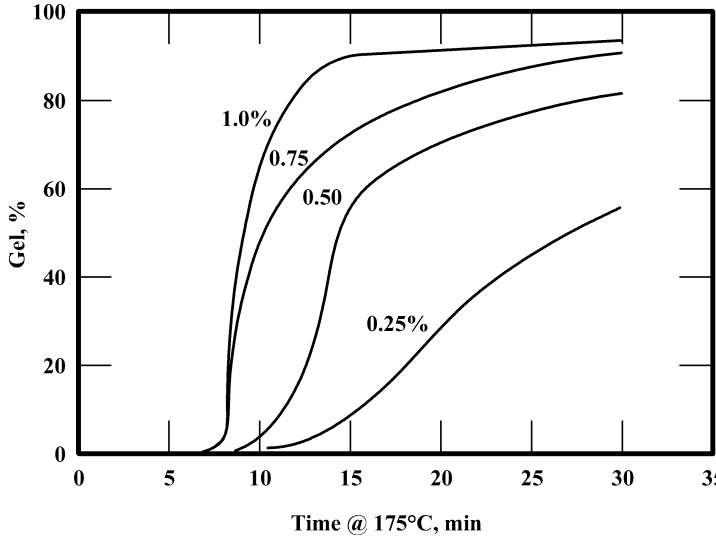

Figure 2.12 Time-dependent gel formation of peroxide crosslinking of HDPE, redrawn from Ref. 47, with permission of John Wiley & Sons, New York. Crosslinking agent is 2,5-Dimethyl-2,5-di(tert-butylperoxy)hexyne

2.10.3.8 *Weathering*

Most rotationally molded parts are used outdoors, as chemical tanks, trash containers, and playground equipment. All plastics are sensitive to ultraviolet radiation. Surprisingly, polyethylene is not one of the most stable polymers for exterior application.* It can be degraded by outdoor exposure, particularly at high temperatures, higher elevations where UV or acid rain is particularly intense, and with certain pigment and additive packages. Recently, laboratory accelerated weathering devices have become quite reliable in predicting natural environmental conditions.[48] ** To ensure reliability:

- Laboratory tests must include samples of material of known weather resistance. One sample should have been run in the laboratory weathering tester, and another should have been tested in an outdoor weatherometer that meets ASTM D-1435.
- The laboratory device must include both natural UV wavelengths and moisture. The device must also be capable of running either type of weathering independently to determine material sensitivity to one or the other.
- Plots of hours of weatherometer testing against months of "standard" actual exposure should never be considered as universal, since the particular product may encounter natural environmental conditions that differ widely from the standard.

Table 2.15 gives relative weather resistance for several polymers. Many UV additives such as hindered amines, benzophenones, and carbon black, dramatically extend the useful life of many of these polymers.

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* PMMA or acrylic is probably the most stable polymer used in outdoor applications, as evidenced by its extensive use in signage. Rigid PVC when properly modified, is also used extensively as siding and window fascia in building construction.

** There are many outdoor accelerated test standards. Of particular interest to rotational molders are ASTM D-4364, "Standard Practice for Conducting Accelerated Outdoor Weathering of Plastic Materials Using Concentrated Natural Sunlight," ASTM G-90, "Standard Practice for Performing Accelerated Outdoor Weathering of Non-Metallic Materials Using Concentrated Natural Sunlight," ISO 877, "Plastics — Methods of Exposure to Direct Weathering, to Weathering Using Glass-Filtered Daylight, and to Intensified Weathering by Daylight Using Fresnel Mirrors," and JIS Z-2381, "Recommended Practice for Weathering Test."

Table 2.15 Weather Resistance of Rotationally Molded Polymers (Adapted from Ref. 49)

- *Excellent Resistance*
  Acrylics, PMMA, FEP, PTFE, fluoropolymers
- *Average Resistance*
  Polycarbonate, polyesters, cellulose acetate butyrate [CAB], cellulose acetate propionate [CAP], nylons, linear polyurethane, modified polyphenylene oxide [mPPO], rigid PVC
- *Poor Resistance*
  Polyethylenes, polypropylenes, polystyrene, acetal [POM], cellulose acetate [CA]

2.10.3.9 *Odor in Plastics*

Certain plastics, such as polypropylene have a peculiar odor when processed. Other polymers, such as polyethylenes, acquire an odor when crosslinking agents are used. Two general classes of odor tests are used in rotational molding. The simpler test uses a "standard panel." The freshly rotationally molded part is sealed and kept for several days in an elevated-temperature environment. The part is then unsealed and several people with particularly good abilities to identify "standard odors," such as lemon oil, banana oil, sour milk, rancid butter, and paraffin wax, sniff the interior air. Without discussion, each person notes his or her impression of any odor. The intensity of the odor is also noted. Gas chromatographic or GC sampling of the interior air is a more sophisticated albeit more complex and expensive test. GC will yield a technical analysis of the odor that frequently can be related back to the various ingredients in the plastic.

2.10.3.10 *Fire Retardancy*

In certain instances, rotationally molded plastic parts must meet certain fire resistance standards. There is always concern that the high oven temperatures and long times in rotational molding may compromise the fire retardancy of the as-purchased polymer. Many agencies have fire and flammability requirements and there are many testing protocols that are used to compare the plastic part with these requirements. ASTM lists at least 14 test protocols alone.

There are two types of tests. One deals with the fire performance of the product itself. The other deals with the fire performance of a test specimen. Probably the most used product-oriented test is Underwriters Laboratory [UL] E-84 tunnel test.[50] Panels are placed along the ceiling of a 20-inch × 24-ft

tunnel. Gas burners are lit on one end of the tunnel and the rate at which flame propagates along the tunnel ceiling is measured. A flame-spread rating is given to the plastic. A value of zero is equivalent to asbestos board. A value of 100 is equivalent to red oak flooring. At the exhaust end of the tunnel, the smoke density and sometimes the smoke chemical make-up are monitored. A smoke index is also assigned to the plastic. A value of 100 is equivalent to red oak flooring. Many building codes do not approve the use of plastics with flame spread ratings of more than 200 or smoke ratings of more than 500. The tunnel test has been used to evaluate rotationally molded products such as institutional furniture.

Fire testing on samples usually focuses on flame propagation or the level of oxygen needed to sustain combustion. The "standard match" test is typical of a laboratory test for flammability. A prepared, conditioned sample is held vertically over a burner. Flame is applied for a fixed period of time, then removed. The time required to extinguish the flame is monitored and any dripping is noted. The procedure is repeated several times. A rating is then given to the plastic. For UL 94 or ASTM D-3801, a "V5" rating indicates that the plastic is quite fire retardant, whereas a "V-2" rating indicates that it supports flame for an extended period of time.[51] In the oxygen index test, ASTM D-2863, a plastic specimen is held vertically in a glass cylinder. The air in the cylinder is purged with pure oxygen and the plastic specimen is ignited with a butane or propane torch. Once the plastic is burning steadily, the oxygen content in the cylinder is gradually lowered. The oxygen index is the amount of oxygen needed to sustain combustion. If the oxygen index for a given plastic exceeds about 25%, the plastic is considered to be nonburning.* Table 2.16 gives typical oxygen index values for several rotationally molded plastics:

Table 2.16 Oxygen Index Values for Plastics. See Also Ref. 52

Polymer	Oxygen Index, %
PTFE	95
Rigid PVC	40 to 47
Nylon 66	28
Polycarbonate	22 to 27
Polystyrene	18
Acrylic	17
Polypropylene	17
Polyethylene	17
Acetal or POM	15 to 16

* The oxygen content of air is 21%.

2.11 Desirable Characteristics of a Rotational Molding Resin

As more and more resins become available to the rotational molder, it may become difficult to cope with a broad range of processing characteristics.[53–55] The physical nature of the resins may vary in terms of the quality of the powder (different particle shapes, distributions, etc.) as well as different forms — granules, micropellets, liquids, etc. Also, the rheological characteristics of the materials may be quite different in terms of their melt viscosities, elasticities, etc. So this begs the question "Can we define the best characteristics in a rotational molding resin?" Unfortunately there is no simple answer to this, although from past experience and recent research results we can identify some of the features that are desirable to make a resin amenable to rotational molding.

The desired physical nature of a rotational molding powder is considered in detail in Chapter 3 and the characteristics of rotationally moldable liquids are described in Chapter 6. At this stage a few comments will be made on the rheological characteristics that are required. Although the melt behavior of plastics is defined by the standard Melt Index test as discussed earlier, in fact this is not entirely relevant to rotational molding. The reason is that in the Melt Index test the shear rates on the melt are considerably higher than are experienced during rotational molding. As a result it is quite possible to have two resins that exhibit the same Melt Index but behave differently during rotational molding. In order for a plastic to perform well in rotational molding it should have a low zero shear viscosity. The test to measure this property is more expensive than the Melt Index test but it represents a much more useful way to rank resins for rotational molding.[56]

In addition, it is important that the resin attains its low zero shear viscosity very soon after it melts. Some resins that do achieve a low viscosity at higher temperatures may have a high viscosity when they first melt. This sometimes leads to levels of porosity that are difficult to overcome during the rotational molding cycle.

Another important factor in rotational molding resins is that the elasticity in the polymer melt should be low. If a melt has a high elastic modulus component, it has been shown[56] that this leads to poor coalescence of powder particles and high levels of porosity in the rotationally molded part. As the rotational molding industry expands into new market sectors it is evident that greater demands are being placed on the materials used to manufacture the parts. The unique nature of rotational molding with its long cycle times and low shear during shaping means that special attention needs to be paid to the development of materials with the particular characteristics referred to above.

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3 GRINDING AND COLORING

3.0 Introduction

The materials used in rotational molding can be in a variety of forms, depending on the nature of the plastic. For example, coarse granules can be used with some types of nylon because this material melts very rapidly. Liquid PVC plastisols have been in use since the earliest days of rotational molding because liquid readily coats the inside of the mold. Liquid forms of caprolactam (nylon) and other materials such as polyurethane,[1–3] certain epoxies,[4] and silicone[5] have also been used very successfully. However, the vast majority of materials used in rotational molding are in powder form.

The polyethylene material used for rotational molding is always in the form of powder or micropellets.[6, 7] The latter material form is a relatively recent development and although it has many attractive features, powder still accounts for over 95% of the polyethylene used. Powder is produced by pulverization, sometimes also called *grinding* or *attrition*.[8–11] There are many ways to grind brittle and high modulus materials such as ores and minerals. Some high-modulus polymers are hammer-milled or ball-milled, but the majority of polymers are ground between rotating metal plates.

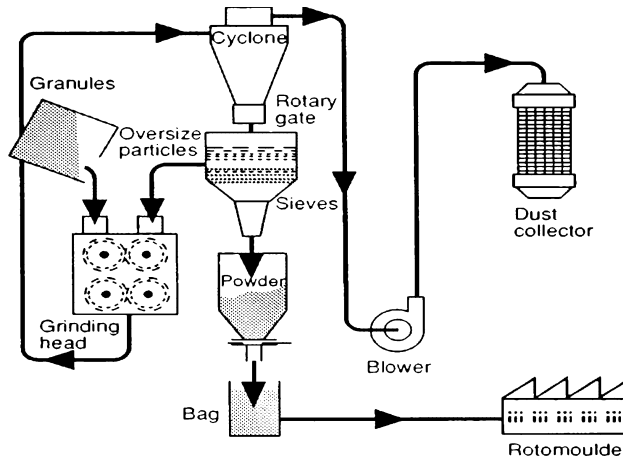


Figure 3.1 Stages in the grinding of powders for rotational molding, redrawn from Ref. 11, used with permission of The Queen's University, Belfast

The basic stages in the grinding of polymers for rotational molding are illustrated in Figure 3.1. Pellets are fed into the throat of the mill from a feed hopper by means of a vibratory feeder (or auger) at a uniform and controlled rate. As these pellets enter the mill, along with a flow of air, they pass between two metal cutting plates, each with a series of radial cutting teeth. Figure 3.2 shows the construction of a vertical grinding head. Figure 3.3 shows a side view of the cutting teeth.

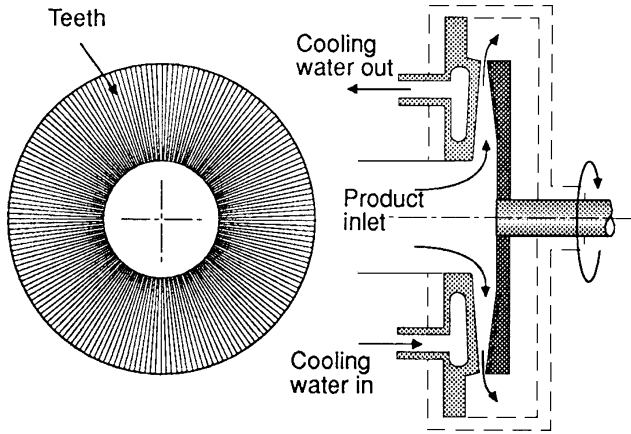


Figure 3.2 Typical vertical mill grinding plates for plastic powders,[11] used with permission of The Queen's University, Belfast

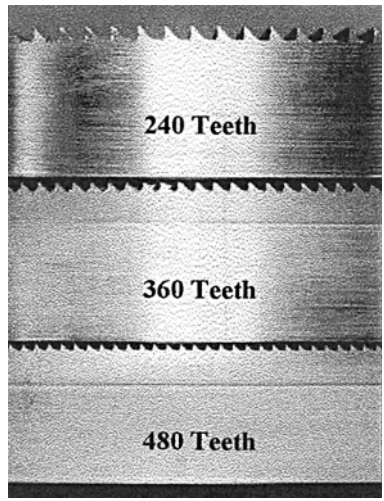


Figure 3.3 Side view of cutting plates with different numbers of teeth,[11] used with permission of The Queen's University, Belfast

The teeth on the rotating plate are cut at an angle (typically 4°) so that the gap between the cutting edges of the two plates is narrower at the periphery. When the pellets enter the mill, centrifugal force pushes them out between the cutting plates. Each pellet is slowly reduced in size as it is carried outward into the narrowing gap between the two cutting faces. The particles remain between the plates until they are of a size that allows them to escape from the gap at the periphery.

In the grinding process, frictional heat increases the temperature of the metal cutting faces, the individual polyethylene particles, and the surrounding air. As a consequence, the temperature must be controlled so that it does not rise beyond the melting point of the polyethylene or to a critical softening temperature, prior to melting, when the particles begin to adhere to each other. This can cause blockages in the passage of new material entering the mill.

Once the particles exit the mill they go into an air stream which conducts them to a screening unit containing a number of sieves of a standard mesh size. Particles that pass through the screens are taken out of the system and collected as usable powder. Those particles that do not pass through are conveyed back to the mill and reground. Figure 3.4 illustrates the path taken by particles through the screens in the classifier.

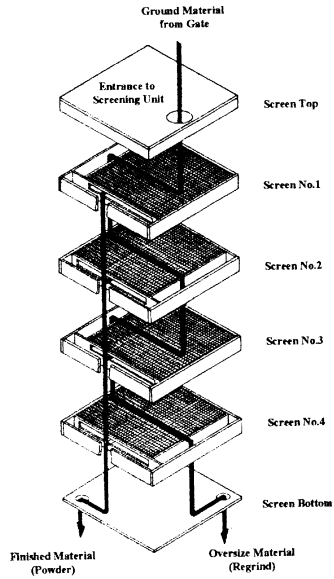


Figure 3.4 Path by particles through the screen pack,[11] used with permission of The Queen's University, Belfast

Modern grinding systems are PLC-controlled. A drop in air pressure, an increase in the temperature, or an ampere overload of the drive motor will result in a decrease of material intake from the feeder. The feed of granules is allowed to increase if all the above factors are within set limits. A typical system is illustrated in Figure 3.5.

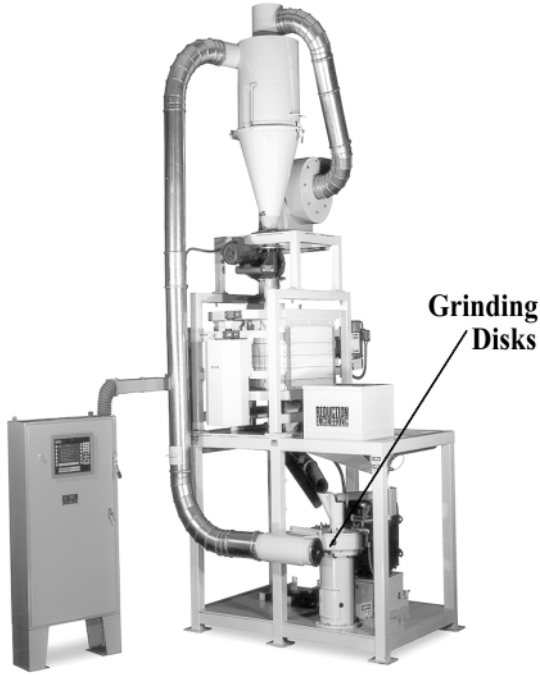


Figure 3.5 Typical grinding mill for polyethylene, used with permission of Reduction Engineering, Canton, OH

Industrial grinding machines may have two grinding mills in line. The gap size between the first two mill plates is relatively large compared to that for the second. The purpose of the first mill is to reduce the overall size of the particles going into the second mill. The gap size on the second mill is set so as to yield the desired particle size distribution. This improves efficiency, and allows for a higher production rate by decreasing the amount of regrind (oversize particles) that is returned to the mill.

Although vertical disk attrition mills, as illustrated in Figure 3.2, have been used for polymers for many years, the horizontal disk mill, as shown in Figure 3.6, is being widely used today. This set-up ensures more even wear on

the grinding plates and hence better quality output. One disk is stationary, actively cooled, and moves for gap adjustment. The second disk rotates and is usually not actively cooled, because it is self-cooling much like a fan impeller. The disk faces are hardened and may be grooved, serrated, or roughened. Pellets are volumetrically metered into the mill through a vibratory feeder and into the center of the stationary disk. Variables such as the mill grinding temperature, the motor amperage, the vacuum in the takeaway system, and the state of the vibratory feeder are continuously monitored in order to facilitate process control.

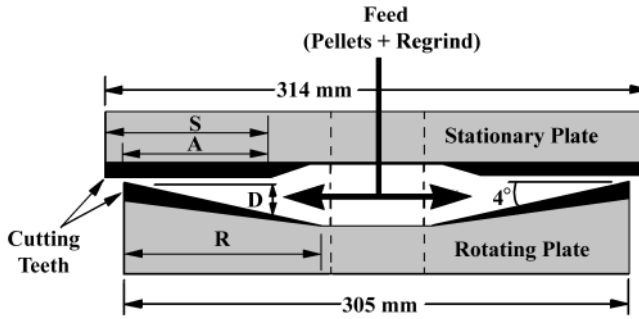


Figure 3.6 Typical horizontal plates for rotational molding powders,[11] used with permission of The Queen's University, Belfast

3.1 General Issues Relating to Grinding

In the early days of rotational molding, grinding of pellets or granules was thought to be necessary only to produce small particles that would flow well in the mold.[8] Other advantages that the particles were considered to have over granules included the ability to get extra weight of plastic into the mold for the same volume of material, and the ability to melt down more rapidly. However, in more recent times the importance of having a high quality ground powder has increased significantly. Specifications for the powder for rotational molding have narrowed in the search for higher productivity, better surface quality, and shorter molding cycles. Added to this are the requirements for traceability of quality parameters as a consequence of the introduction of ISO Quality Standards.

The grinding of polymers between high speed rotating plates involves the physical cutting and tearing of particles from the surface of granules. The powder particles thus formed are not regular in shape or size. Figure 3.7 shows some granules taken from between the grinding plates. This illustrates how the particles are torn away from the surface of the granules.

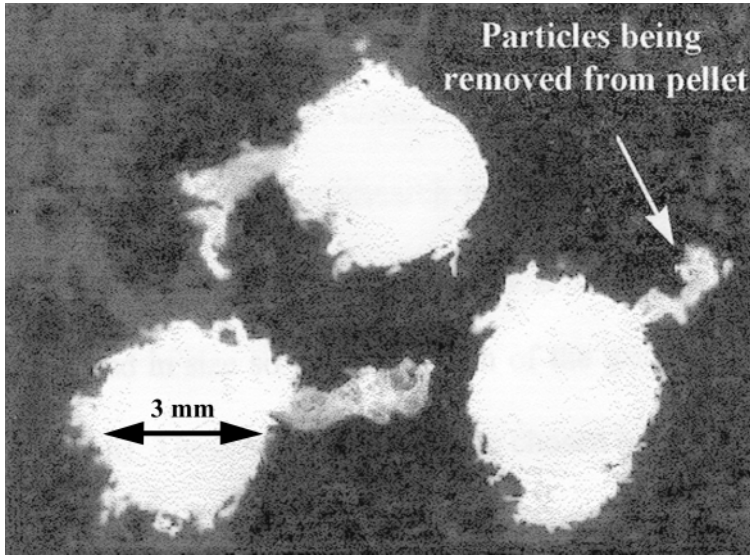


Figure 3.7 Formation of powder particles from granules

The most common parameters used to define the quality of a powder for rotational molding are:

- Particle size distribution (PSD)
- Dry flow
- Bulk density

Typical figures for the properties of LLDPE powders used in rotational molding are:

- PSD 95% < 500 μm with maximum 15% < 150 μm
- Dry flow <27 seconds
- Bulk density >320 kg/m^3

A good balance of these parameters provides the molder with a material that meets the following key requirements:

- Good heat transfer
- High initial bulk density
- Good cavity filling
- Less pinholes
- Good surface finish quality
- Limited degradation in the mold
- No dusting

Due to the importance of particle size distribution, particle shape, the dry flow, and the bulk density to successful rotational molding, these aspects are considered in detail in the following sections.

3.2 Particle Size Distribution

In the rotational molding industry, the particle size of powders is usually quantified in terms of the mesh size. This relates to the number of mesh openings per inch in the sieve used to grade the powder. Table 3.1 gives some of the mesh sizes defined in the British and American standards.

Table 3.1 ASTM E-11 U.S. Sieve Sizes

Tyler Size	Sieve Opening (× 0.001 inch)	Wire Diameter (× 0.001 inch)	Particle Size (microns, μm)
35	16.5	11.4	420
60	9.8	7.1	250
80	7.0	5.2	177
100	5.9	4.3	149
115	4.9	3.6	125
150	4.1	3.0	105
170	3.5	2.5	88
200	2.9	2.1	74
250	2.5	1.7	63
325	1.7	1.2	44
400	1.5	1.0	37

A 35 mesh (500 μm) powder has the typical particle size distribution used in rotational molding. Although there have been few studies on the ideal particle size distribution, it is generally accepted that powders having a narrow size distribution under 500 microns offer the best compromise between grinding costs and the fusion characteristics of the plastic. Some typical commercial particle size distributions are given in Section 3.2.2.

Before going into the detail of particle size analysis, a few general comments can be made in regard to the types of powders needed for rotational molding. The desired particle size distribution should provide good packing of the different particle sizes. This helps to reduce voids between particles, thereby minimizing surface porosity and the tendency to trap air bubbles in the melt. Very fine powders have greater surface area-to-volume and so are more susceptible to thermal deterioration. Also, since fine powders tend to fluidize

more readily and do not flow as well, heating cycle times can be extended. The problems with airborne dust during mold filling are exacerbated by fine powders. Very coarse powders, on the other hand, lead to increased heating cycle times and irregular, matte outer surfaces with many pin holes. In the past it was thought that undesirable tails are generated on the powder particles by using high grinding temperatures. However, there is now strong evidence that this is not true.[11] The effects of grinding variables on the quality of the powder will be discussed in Section 3.6.

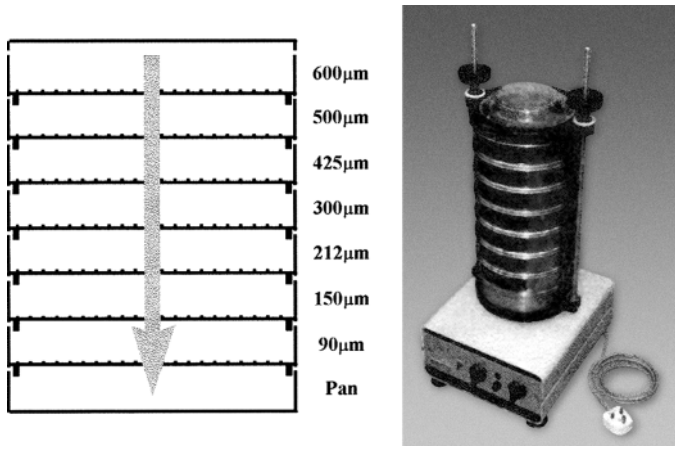


Figure 3.8 Typical sieve shaker used for rotational molding powders

The particle size distribution of rotational molding powders is measured according to ASTM test method D-1921. A set of nested, stacked, welded wire sieves, with mesh sizes ranging from about 35 mesh to 200 mesh is used for this determination.[12] Basically, a thief of powder is taken from a representative bag or gaylord, weighed, and placed in the top sieve of the sieve stack. The shaker is covered and mounted in a device that rotates, shakes, and vibrates, as shown in Figure 3.8. After a predetermined period of time, the sieves are separated and the amount of powder retained on each sieve is weighed. The powder that passes through the bottom sieve into the retaining tray is measured as well. There is a continuing debate as to the length of shaking time required to reach a final particle size distribution. Ten to fifteen minutes is considered sufficient for powders that have compact shape and no static charge build-up. It has been found that for acicular powders, powders with high static charge, and powders that have shapes that tend to interlock or bridge, the particle size distribution continues to change even after four hours of shaking.

Particle size distribution inaccuracies occur when the screens are blinded by the powder, implying static charge build-up or high concentrations of tails. Errors can also occur when powder that passes through a screen is statically held against the underside of the screen and is not recorded in the correct size band.

3.2.1 *Particle Size Analysis*

Although vibratory sieves of the type described above are the most commonly used in the rotational molding industry, there are other ways of measuring particle size distribution (PSD). It is important to recognize that the same sample of powder may record different PSD's in different measuring devices.[13] This is partly because the shape of the particles can affect the readings. As an illustration of this, long needle-like particles find it difficult to pass through mechanical sieve apertures. Therefore, although there may be a range of lengths of these particles, they are all recorded as large because they cannot pass through the sieve. In contrast, noncontacting measurement methods that rely on assessing an image of the particles may record such particles as long or very short, depending on how they are aligned to the viewing position. It is important therefore to remember that the PSD for a particular sample of powder is not a unique value. It will depend on the method used to take the measurement. When the measurement of PSD is part of the regime of quality control it is therefore important to be consistent in the type of equipment that is used. It is also important to ensure uniform test methods are employed as it is not uncommon for different operators to get different readings from the same sample on the same equipment.

The following sections consider the various types of particle size analyzers that are available in the marketplace.

3.2.1.1 *Dry Sieves*

Types of dry sieves include:

- High-speed, low-amplitude vibrating screens
- Using mechanical vibrational means at about 20 vibrations per second
- Using electrical vibration at vibrations of 25 to 120 vibrations per second
- Mechanical or pneumatic screen stacks
- Centrifugal screens operating at 300 to 400 rev/min

As discussed above, the time required to reach reliable particle size

distributions for mechanical shaking devices depends on many factors. These include:

- Characteristics of the particle (shape, static charge)
- Particle load on the sieve
- Method of shaking the sieve
- Geometry of the sieve surface (welded wire, perforated plate) and its wear
- Angle of presentation of the particle to the aperture

3.2.1.2 *Elutriation*

In elutriation, the powder is air-lifted through a series of decreasing diameter screens. The air-lifting can be continuous or pulsed. After about 5 to 10 minutes, the airflow is stopped. The segregated particles settle on the screens below. These devices are sometimes called *sonic sifters*.

3.2.1.3 *Streaming*

In this method, the particles are suspended in either air or water and caused to flow past a detector. The detector measures the perturbation caused by the particles. The detector can be a laser beam or if the particles are electrically charged, the detector can measure electrical resistance. These devices can measure particles to less than 1 micron, but must be carefully calibrated and the particle dosage in the stream must be very low to minimize coincidence error. Some streaming devices can be used to measure particle shape as well as size.

3.2.1.4 *Sedimentation*

In this case, the particles are suspended in water, or other liquid, and they settle (or rise) at rates dependent on the density difference between the polymer and the liquid and on the particle diameter, according to Stokes equation:

$$U_{\text{Terminal}} = \frac{gD^2_{\text{particle}}(\rho_{\text{particle}} - \rho_{\text{fluid}})}{18\mu} \tag{3.1}$$

where U_{Terminal} is the terminal velocity, g is gravity acceleration, D_{particle} is the particle diameter, ρ_{particle} and ρ_{fluid} are the densities of the polymer particle and fluid, respectively, and μ is the Newtonian viscosity of the fluid. Light scatter-

ing devices can accurately determine particle size distribution, so long as the particle dosage in the fluid is very low and the particles are greater than about 50 microns.

3.2.1.5 *Fluidization*

This technique is similar to sedimentation except that air is used as the fluid medium. The Stokes equation holds and photo-densitometer techniques yield reliable particle size distribution, again so long as the particle dosage in the air is very low.

3.2.2 *Presentation of PSD Data*

It is evident that there is no absolute definition of the best particle size distribution for rotational molding. It is difficult to isolate PSD from other variables and so suppliers and molders have reported a variety of PSDs that give good results. Table 3.2 gives details of three types of distributions that have been used successfully by molders.

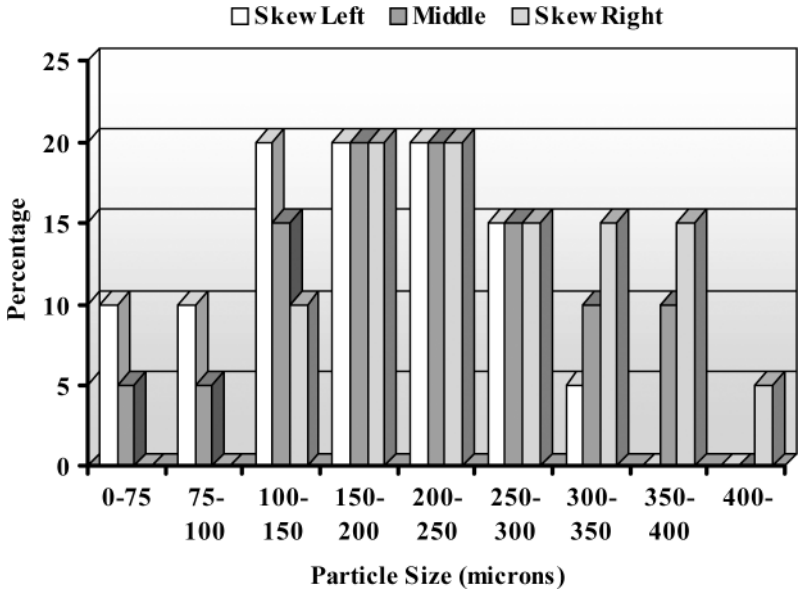


Figure 3.9 Histogram of typical particle size distributions

Table 3.2 Typical Particle Size Distributions Used in Rotational Molding

Particle Size (microns)	Skewed Right (%)	Middle (%)	Skewed Left (%)
<75	0	5	10
75–100	0	5	10
100–150	10	15	20
150–200	20	20	20
200–250	20	20	20
250–300	15	15	15
300–350	15	10	5
350–400	15	10	0
>400	5	0	0

There are two accepted ways of plotting the particle size distribution. Individual particle "cuts" are usually plotted in a histogram, as shown in Figure 3.9. The cumulative percentage distribution method presents the cumulative percentage against mean cut size as illustrated in Figure 3.10. In this presentation, the median is read as the 50% cumulative percentage. Both Figures 3.9 and 3.10 relate to the data in Table 3.2.

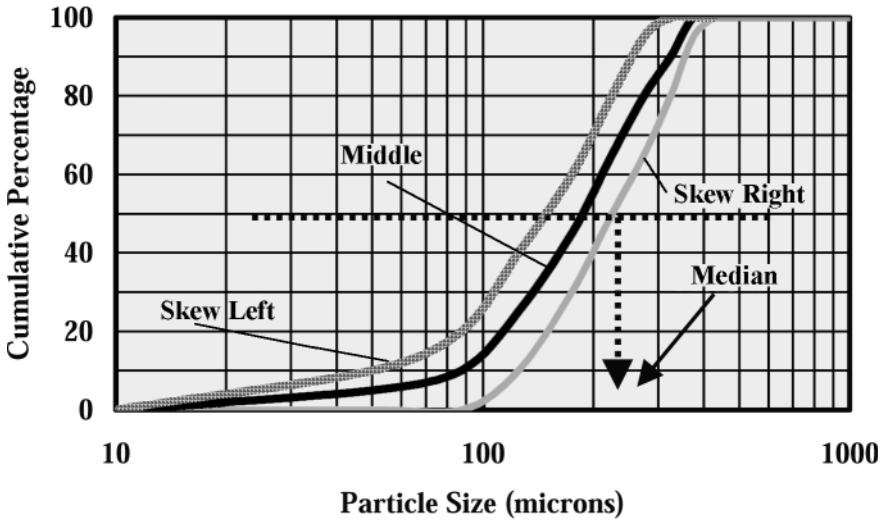


Figure 3.10 Cumulative percentage plot of typical particle size distributions

3.3 Particle Shape

In general, particle shapes range from spherical to acicular or fiber-like. Neither extreme is acceptable for rotational molding powders. It was originally suggested by Rao and Throne[14] that the most desirable shape for a rotational molding particle is a "squared egg." That is, the particle should be ovoid in side projection but rectangular or square, with generous radii, in end projection (Figure 3.11). Spherical particles should be avoided since their packing density is low and the particle-to-particle contact is point-like rather than areal. Acicular particles should also be avoided due to excessive porosity and bridging in the formed part.

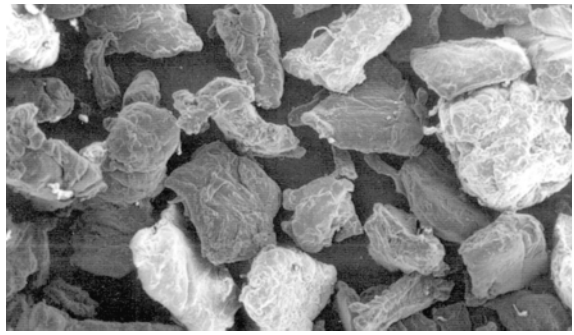


Figure 3.11 Good particle shapes for rotational molding powders,[10] used with permission of The Queen's University, Belfast

There are many ways[15, 16] of classifying particle shape (Figure 3.12). One of the simplest is the shape factor, being the ratio of the surface area of a sphere equal in volume to the particle to the surface area of the particle. Other ways are given in Table 3.3. As is apparent, many of these shape factors depend on the two-dimensional projected image of the particle, Figure 3.13.

Figure 3.12 Typical particle dimension

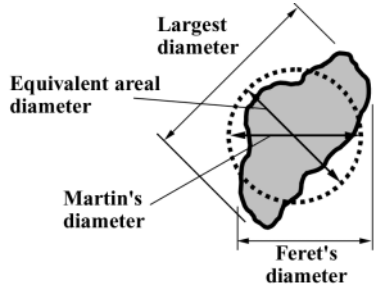


Figure 3.13 Microscopic size factors

Table 3.3 Shape Terms for Irregular Particles

Average thickness	The average diameter between the upper and lower surfaces of a particle at its most stable position of rest.
Average length	The average diameter of the longest chords measured along the upper surface of a particle in the position of rest.
Average breadth	The average diameter at right angles to the diameter of average length along the upper surface of a particle in its position of rest.
Chunkiness	Reciprocal of elongational ratio.
Circularity	Ratio of the circumference of a circle with the same projected area to the actual circumference of the projected area.
Elongational ratio	The largest particle length to its largest breadth when the particle is in a position of rest.
External compactness	The square of the diameter of equal area to that of the profile, divided by the square of the diameter of an embracing circle.
Feret's diameter	The diameter between the tangents at right angles to the direction of scan, which touch the two extremities of the particle profile in its position of rest.
Martin's diameter	The diameter which divides the particle profile into two equal areas measured in the direction of scan when the particle is in a position of rest.
Projected area diameter	The diameter of a sphere having the same projected area as the particle profile in the position of rest.
Roundness factor	Ratio of the radius of the sharpest corner to the most round corner with the particle in a position of rest.
Specific surface diameter	The diameter of the sphere having the same ratio of external surface area to volume as the particle.
Surface diameter	The diameter of the sphere having the same surface area as the particle.
Stokes diameter	The diameter of the sphere having the same terminal velocity as the particle.
Volume diameter	The diameter of the sphere having the same volume as the particle.

For rotational molding grade polymers, the particle sizes are easily seen and photographed through 30× magnifiers. A linen magnifier is a simple and inexpensive magnifier that can be used on the production floor. The science of determining three-dimensional structural parameters from the two-dimensional measurement of features in the planar surface is called *stereology* or *morphometry*. Basically it assumes that the features in the cross-plane are similar or identical to the features in the projected plane. Technically, this is valid for objects such as spheres and cubes, but invalid for cones, for example. Nevertheless, on the average, conversion of two-dimensional features to three-dimensional features is reasonably accurate for the model "squared-egg" particle, particularly when hundreds of particles are analyzed.

Particle shape can be determined by manually examining photographs of many particles, or by computer-based image analyzers. These devices raster scan a magnified field of many particles. The scan is then fed to a computer program that determines the particle characteristics according to shape, as given in Table 3.3, and size, for comparison with mechanical sieving techniques. One well-known analyzer is the Coulter counter, used extensively in biomedical research for analyzing blood and bacteria characteristics. Other devices are made by optical companies such as Zeiss, Cambridge-Quantimat, Leitz, Millipor, Bausch and Lomb, and Hamamatsu. Particle size analyzers cost $25,000 or more and are normally part of the analytical support package offered by advanced polymer powder processors.

A careful examination of particle shapes of five commercial rotational molding grade polyethylenes shows elongational ratios of about 1.5 to 2.3, chunkiness factors of 0.45 to about 0.6, circularity values of 0.7 to 0.8, and roundness factors of 0.1 to about 0.25.[17] For a perfect sphere, the values for all these factors are unity. The values of these factors are very close to those for the ideal particle shape of a "squared egg" identified 25 years ago. Furthermore, the values of these factors seem to be nearly independent of particle size.

3.4 Dry Flow

Powder dry flow properties are important during rotational molding as they determine how the polymer distributes itself within the mold and how well the polymer melt flows into complex shapes. Dry flow depends mainly on particle size and particle shape. Since the particle size distribution of a 35 mesh powder tends not to vary greatly, it is the particle shape that has the greatest effect on dry flow. The presence of tails on powder particles reduces dry flow prop-

erties, leading to detrimental part properties such as bridging across narrow recesses in the mold and high void content within the part wall.

The standard method for measuring the *dry flow* of a powder is described in ASTM D-1895. It is the time taken for 100 g of powder to flow through a standard funnel. The dry flow is quoted in seconds. The equipment used is shown in Figure 3.14. Note that the dimensions given are for guidance only — the accurate dimensions are given in the Standard.

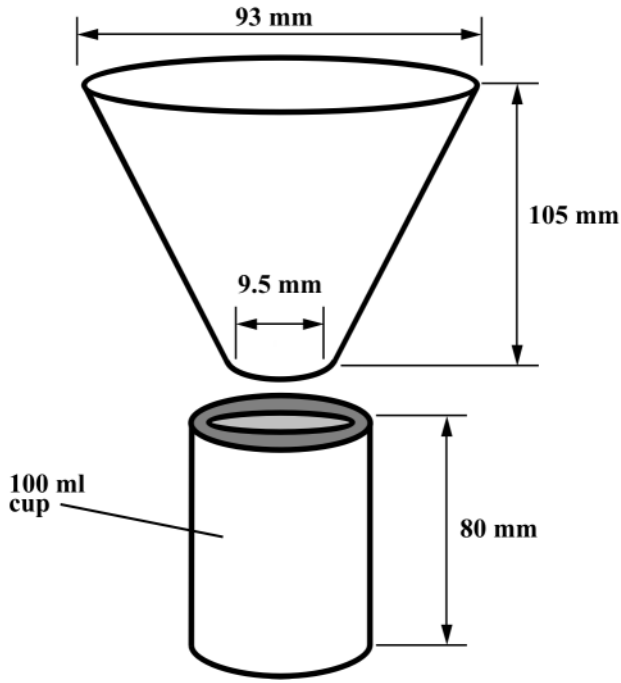


Figure 3.14 Dry flow and bulk density apparatus

3.5 Bulk Density

Bulk density is a measure of the efficiency with which the powder particles pack together. A good quality powder having "clean" particles with no tails will have a high bulk density. Bulk density and dry flow are dependent on the particle shape, particle size, and particle size distribution of the powder. These

two properties are inversely related, in that an increase in the bulk density corresponds to a faster dry flow rate, as shown in Figure 3.15.

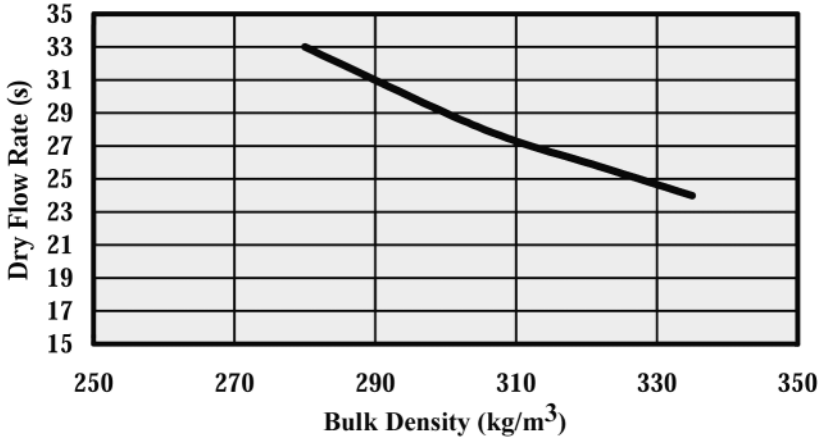


Figure 3.15 Variation of dry flow rate with bulk density for rotomolding powders

3.5.1 *Packing of Particles*

As discussed earlier in this Chapter, rotational molding grade powders are typically in the range of 200 mesh to 35 mesh (or -75 microns to 420+ microns). Grinding operations usually yield a Gaussian distribution as shown in the histogram and cumulative percentage plots (Figures 3.9 and 3.10). This type of distribution is important to achieve high packing density and intimate particle-to-particle contact during the coalescence step of particle adhesion. The concept that characterizes the importance of particle size distribution is *packing fraction*. This is defined as the ratio of the density of the powder bed to the density of the powder particle. In certain industries, the concept is *void fraction*, being one minus the packing fraction. The easiest way of understanding packing fraction is to consider spheres of equal diameter. If spheres are packed in a cubic mode, as shown in Figure 3.16, the packing fraction is 0.534.[18] In other words, for a powder with spherical particles, if the polymer density is 1000 kg/m^3 then the bulk density of the powder is 534 kg/m^3. This means that the volume occupied by the powder in the rotational mold is nearly twice that of the polymer when melt-sintered on the mold surface. There are of course other ways of packing equal spheres, as indicated in Table 3.4.

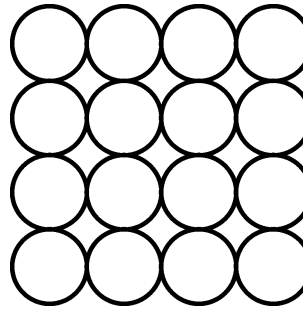


Figure 3.16 Cubic packing of spheres

Table 3.4 Packing Arrangements for Equal Spheres

Packing Type	Void Fraction	Packing Fraction	Coordination Number
Cubic	0.476	0.534	6
Orthorhombic	0.395	0.605	8
Tetragonal-spheroidal	0.302	0.698	10
Rhombohedral	0.260	0.740	12

The *coordination number* is the number of points of contact each sphere has with its neighboring sphere. Of course, rotational molding powders are neither spherical nor of uniform diameter. The bulk densities or packing fractions of particles of mixed sizes and shapes are usually substantially different than the theoretical values quoted in Table 3.4. Whether the packing fraction is greater than or less than the theoretical value depends strongly on the particle size distribution and to some extent on the particle shape. With the exception of highly anisotropic structures such as fibers and plate shapes, there is very little analytical information on the relative effect of particle shape on packing fraction. Since rotational molding powders are relatively free of these structures, it can be assumed that the packing fractions for "squared-egg" type shapes are relatively close to those for spheres. Figure 3.17 shows a micrograph looking down into a void or pinhole in a rotationally molded part.[11] This shows how particles approximately 30–40 mm in size are packing together.

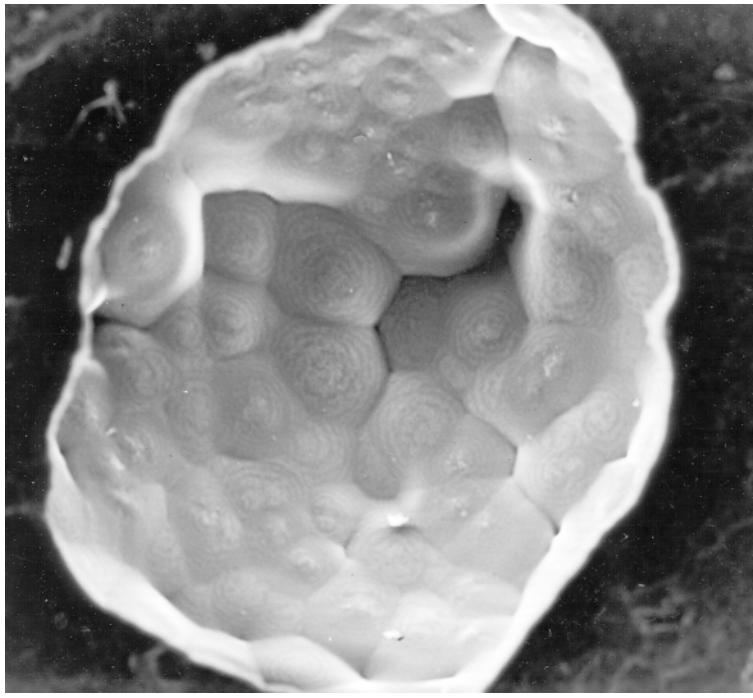


Figure 3.17 Micrograph of interior of bubble in rotationally molded part

The nature of the particle size distribution can strongly influence the bulk density. When fine particles are mixed into coarser ones, they act in two opposing ways. They tend to separate the coarser particles and they tend to fill in the interstices between the coarser particles. The former effect acts to reduce the bulk density, whereas the latter increases the bulk density. When the weight ratio of fine particles to coarse particles exceeds 3:1, the former effect dominates. Theoretically, it can be shown that for five successive specified sizes of particles, a packing fraction of 0.85 can be achieved, but only if each successive particle dimension is 70% of that of the previous particle dimension. Typically, with the same particle size distribution, the packing fraction decreases as the mean particle size decreases. This is due to arching and bridging, which in turn are the result of the greater surface-to-volume ratio of the finer particles. Typically, coordination numbers for mixed particle sizes of irregular shapes are in the range of 10 to 20. From a coalescence viewpoint, the coordination number should be as large as possible.

There are three methods of determining bulk density or packing fraction.

One is to pour a weighed amount of powder into a standard container to measure its volume (Figure 3.14). This yields poured bulk density. This is a representative value for bulk density of powder charged to a rotational mold. If the poured powder is now vibrated, the result is a compacted bulk density. This density is representative of the bulk density of the powder in a silo or gaylord. If the vibrated powder in the graduated cylinder is then tamped, the resulting density is representative of the density of the coalesced powder adhering to the mold surface, prior to densification. It must be remembered, however, that prior to coalescence against the mold wall, the powder is freely flowing and a substantial portion of the fines may be fluidized. It has been determined that the packing fraction of a fluidized bed of substantially uniform spheres is on the order of 0.54. The packing fraction does not increase significantly (to 0.56 to 0.60) even when the bed is allowed to settle. For most commercial rotational molding powders, the packing fractions in Table 3.5 can be used.

For rotational molding powders, the *bulk density* is measured according to ASTM D-1895, and the equipment used is illustrated in Figure 3.14.

Table 3.5 Approximate Packing Fractions for Commercial Rotational Molding Powders

State	Packing Fraction Range
Fluidized	0.55–0.60
Poured	0.60–0.65
Vibrated	0.65–0.70
Tamped	0.70–0.80

3.6 Factors Affecting Powder Quality

The production of a good quality powder for rotational molding is not a trivial matter. There are many process variables and these will affect the nature of the powder in different ways and to varying degrees. Some of the main grinding variables were identified earlier. A more complete list includes factors such as:

- Gap between the disks
- Feed rate of granules
- System pressure
- Desk design
- Disk speed

- Choice and type of feeder
- Cooling efficiency
- Operating temperature
- Moisture control
- Air velocity
- Amount of recycle
- Type of auxiliary equipment used
- Amperage of the mill
- Sieve aperture in the screen unit

Research[11, 19] has shown that three of the main factors that affect grind quality are:

1. Gap size between the grinding plates
2. Number of teeth on the grinding plates
3. Grinding temperature (measured at the grinding head)

3.6.1 *Gap Size*

The size of the gap between the two grinding plates has a large effect on the particle shape,[20] the particle size distribution of the powder, and on the efficiency of the process.[11] Increasing the gap size produces more elongated particles and shifts the particle size distribution curve to the right, corresponding to an increase in the average particle size. Gap size also has an important influence on process efficiency. As the gap size increases, the percentage of oversize particles increases. These particles are returned to the grinding plates and hence the input of fresh granules from the feeder decreases. For continuity, the input from the feeder equals the output from the system and so the output decreases as the amount of recycled powder increases. Therefore, as the gap is increased, the output rate of usable powder decreases.

The dry flow and bulk density values have a small dependency on gap size. The fastest dry flow rates and highest bulk density values are found at a gap size of 0.35 mm, with a small decrease in both properties up to a gap size of 0.85 mm. Small improvements seen after 0.85 mm are attributed to the high percentage of large particles in the powder. It is apparent therefore that for any grinding system, there will be an optimum gap size based on a compromise between the desired particle size distribution, the dry flow, the bulk density, and the maximum output rate.

3.6.2 *Number of Mill Teeth*

Varying the number of teeth on the grinding plates alters the particle size distribution.[9, 10] An increasing number of mill teeth yields an increasing amount of particle breakdown. With the reduced depth between the teeth, there is a decrease in average particle size and a shift in the PSD curve to the left (i.e., toward the smaller end of the spectrum).

The dry flow and bulk density properties improve as the number of mill teeth is reduced. This increase is attributed to the higher percentage of larger particles. Another important aspect of the grinding plates is the sharpness of the teeth. When the teeth get worn there tends to be a greater percentage of the smaller particles.[10]

3.6.3 *Grinding Temperature*

Grinding temperature has the most significant effect on the quality of the powder.[11, 19] The effect on dry flow and bulk density values are illustrated in Figure 3.18.

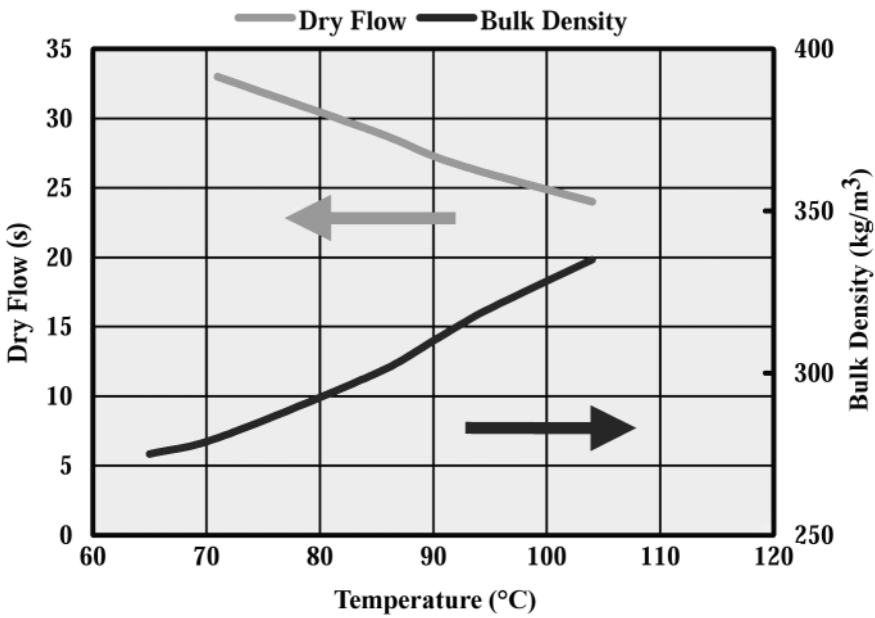
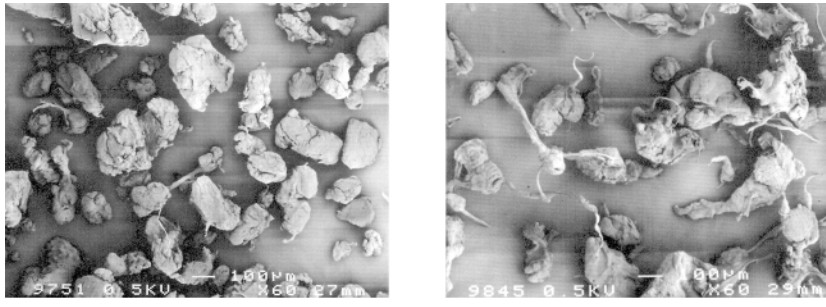


Figure 3.18 Effect of grinding temperature on bulk density and dry flow rate[11, 19]

It may be seen that the dry flow rate improves as the temperature of the powder increases. The time required for 100 g of the powder to flow through the standard funnel was reduced from 33 to 24 seconds when the temperature at the grinding head was raised from 95°C to 104°C. Samples of the powder ground below about 85°C did not flow. The reduction in dry flow times at the higher grinding temperatures is associated with the smoothing of the particles that is known to occur at elevated temperatures.

The removal of tails and hairs from the particles is also reflected in the corresponding increase in the bulk densities. The improvement in particle shape with increasing grinding temperature can be seen in Figure. 3.19. These micrographs show that the particles ground at the higher temperature (on the left) have smoother surfaces and fewer tails. These physical characteristics affect the amount of material that can be placed in the mold, and the flow of the powder when it is in the mold. When the tails are removed from the particles there is a reduced tendency for them to fuse together early and cause "bridging" in narrow recesses in the mold.



High temperature Low temperature

Figure 3.19 Effect of grinding temperature on particle shape[11, 19]

3.7 Grinding Costs

The key to all successful grinding operations is high throughput of good quality powder. The previous Sections have shown that the production of good quality powder depends on many interacting variables. Nowadays it is more important than ever to understand the technology of grinding because many molders are starting to use in-house grinding facilities in an attempt to improve their economics. The decision as to whether it is better to buy powder produced by professional grinders or to set up an in-house facility is not straightforward.

In the design of an up-to-date grinding plant, it is important that molders appreciate the full costs involved. In the cost of producing powder, the following factors have to be taken into account:[8]

- Depreciation costs of the grinding equipment
- Quality control costs
- Depreciation costs of auxiliary equipment
- Power supply costs
- Housing costs
- Maintenance costs
- Warehousing costs
- Insurance costs
- Dedicated manpower
- Administrative costs
- Supervision costs
- Health and safety costs
- Overhead costs
- Environmental costs

Since professional grinders process more material than do in-house grinders and do so on more mills, they are generally more efficient. Also, they obtain better utilization figures of the mills than in-house grinders, consequently costs per kg should be lower.

In addition, professional grinders develop expertise that enables them to exercise close control over the process variables and produce powder to any desired specification. Particular advantages that they can cite include:

- Long experience in optimization
- Sufficient production levels to keep pace with the latest technology
- Dedicated quality control system, aimed at the testing of powders
- Larger equipment to create economy of scale
- Dedicated and skilled personnel
- Responsibility for delivery of the agreed quality

On the other hand, in-house grinding allows more control over costs. There are reduced transport costs and the molder is in control of his/her own destiny in terms of material supplies. Economies of scale can be achieved if large quantities of a particular grade and color are required. Furthermore, modern grinding equipment allows very precise control over process variables. Hence more and more of the larger molders are switching to in-house grinding.

The cost of steady-state toll grinding of pelletized polyolefins to produce rotational molding grade powder is about $0.13/kg for 10,000-kg quantities and more. For cryogenic grinding, the cost can be as much as $0.22/kg for 10,000-kg quantities or more. The in-house cost is about half that of the toll cost. Another way of estimating cost is to determine the throughput capacity of the pulverizer, in kg/h and divide that into $40 to $50/h machine/labor cost to get conversion cost/kg. The set-up and clean-up charges should be included as well. However, in-house pulverization is usually most economical for short runs, of 1000 kg or so.

3.8 Micropelletizing

Although powders dominate the rotational molding industry, they suffer from a number of drawbacks. They are expensive to produce and are not amenable to regular color changes of compounded material. The production of consistent quality powder, in terms of particle shape and particle size distribution requires considerable skill on the part of the grinder. In addition, excessively dry environments lead to very high static charges when powders are dispensed to metal molds. Not only is the static charge dissipation annoying and painful if the molds are not grounded, but powder is attracted to all metal surfaces, leading to a build-up of degraded resin "shellac" on the outside surfaces and mechanisms of the mold and spider. Furthermore, high static charge leads to particle-to-particle repulsion and a lowered bulk density. This is exacerbated by the tumbling motion of the mold just prior to its introduction to the oven. The terminal or settling velocity of 75 micron powders in air is about 2 ft/s (0.67 m/s). Normal air circulation around the servicing station can prevent these particles from settling and may even cause the particles to migrate upward, to coat ancillary equipment with a fine layer of dust. This problem is exacerbated by dry powder blending of colorants, some of which may have particle sizes below 10 microns.

Micropelletizing is one proposed way of overcoming some of these problems.[6, 21] The traditional type of pellet or granule used in injection molding and extrusion is made by extruding the polymer melt through a strand die, into a water bath, and then into a dicer. The resulting granule/pellet shape is a truncated cylinder having a diameter of about 3 mm (0.125 inch) and a length of up to 6 mm (0.250 inch). These pellets are the feed material to the commercial grinding process described earlier.

Micropellets are manufactured in a similar fashion, except that the strand die openings are substantially smaller, with the truncated cylinder diameter being as small as 0.3–0.5 mm (0.012–0.02 inch) and a length of up to 0.6 mm (0.025 inch). Frequently the micropellets are lozenge or ovate in shape. Attractive features of micropellets are their very consistent quality and size. Since micropellets are extruded through fixed-diameter orifices, there is very little variation in particle size. And since micropellets are produced from the melt, the surfaces are typically microscopically smooth. As a result, they flow very easily compared to powders and sometimes are mixed with powders to facilitate filling out of difficult areas of a mold. Molding conditions, such as the rotational speeds and speed ratios, often have to be altered when working with micropellets. This is because micropellets flow very easily over the surface of the mold and this can delay adhesion to some surfaces of the mold wall.

A typical LLDPE extrusion line for producing granules/pellets would consist of a 3½ inch diameter, 32:1 single-screw extruder, a strand die, water bath, and strand cutter. This line can process 250 to 300 kg/h at a die pressure of 1500 lb_f/in^2 (10 MN/m^2). With a micropelletizing die, the throughput of this line is reduced to 75 to 100 kg/h at a die pressure of 2500 lb_f/in^2 (17 MN/m^2). The potential economic attraction of micropellets is that after the extrusion stage they are ready to be introduced directly into the rotational mold, without further processing. However, the relatively low output from micropelletizing lines is one of the major drawbacks that have to be overcome. The low throughputs relative to grinding systems has led to supply problems, and economics that negate some of the potential advantages of micropellets.

Since the typical size of a micropellet is 300–500 microns, these particles have typically twice the linear dimension, and thus 8 times greater volume, than the mean rotational molding grade powder. As shown elsewhere,[22] the efficiency of heating is inversely proportional to the square of the dimension. As a result, heating efficiency of micropellets should be about one quarter that of mean rotational molding grade powder particles. Of course, there are many aspects to powder heating that can minimize this effect, but micropellets have been shown[11] to heat more slowly than powders. Other advantages and disadvantages of micropellets in relation to powders and to conventional pellets are given in Tables 3.6 and 3.7.

Table 3.6 Comparison of Micropellets and Powders for Rotational Molding

Effect	Micropellets	Powders
Particle size distribution	Very narrow (300–500 microns)	35 to 200 mesh (75–400 microns)
Cycle time	Extended	Normal
Porosity	Can be a problem	Normal
Color plate-out or staining	Moderate to low	Moderate to severe
Airborne dust	Low	Can be a nuisance
Color changeover	Recompound, slow	Dry-blend, fast
Color dispersion	Consistent	Can be a problem with certain dry-blending colors
Source of raw material	Extrusion	Extrusion + pulverizing
Pulverizing cost	None	$0.06/lb to $0.15/lb or so
Extrusion cost	Owing to lower throughput, perhaps $0.05/lb to $0.15/lb	None

From the few production evaluations reported so far, micropellets seem useful for severe dusting problems, for high static problems, where liquid dispensing is to be replaced with semisolids, and for large-volume operations. Micropellets are probably not effective where a broad particle size distribution is required, where the part is marginally acceptable for porosity when powder is used, or where custom mixing of colors for very short runs is required.

Table 3.7 Comparison of Micropellet Extrusion with Conventional Granule/Pellet Extrusion

Effect	Micropellets	Conventional Pellets
Throughput	20%-30%	100%
Back-pressure	Can be very high	Normal
Thermal damage	High with excess shear	Normal
Hot strand handling	Very difficult	Normal
Die face cutter speed	Very high	Normal
Cutting blade number	Very high	Normal
Underwater pelletizing	Possible pellet fusion	Normal
Dryer screen size	Very small	Normal
Color dispersion	Excellent	Good to excellent
Pellet static charge	High	Moderate to low

3.9 Polyvinyl Chloride

As discussed in Chapter 2, rotational molding grades of low-durometer PVC are traditionally supplied as an organosol or a plastisol.[23] Pelletized medium-durometer PVCs, with Shore A hardnesses of 85 or more, called drysols, are also available. Recently, low to medium durometer micropellets have been developed. A comparison of micropellet PVC's, liquid plastisols, and drysols is given in Table 3.8.

Table 3.8 Comparison of PVC Rotational Molding Materials

Condition	Plastisol	Drysol	Micropellet
State	Liquid	Dry powder	Micropellet
Dispensing	Liquid pump	Weigh-and-dump	Weigh-and-dump
Ease of dispensing	Moderate	Easy	Easy
Dispensing problem	Slop	Dusty	Little
Clean-up	Difficult, scraping	Moderately difficult	Moderate

3.10 Coloring of Plastics for Rotational Molding

As with all plastics molding technologies, coloring of the end product is often an essential part of the process. In rotational molding there are a number of ways to impart color to the end product. Although painting of polyethylene parts is becoming less problematic,[24, 25] pigmenting the molding is still the main method of coloring rotomolded parts. The pigment can be added as the granules/pellets are being produced by the extruder, and thus the resulting powder will be of the desired color. This is called *compounding* and generally produces the best results. The pigment is thoroughly mixed with the polymer and the properties of the molded part will be better than those produced by any other coloring method. The disadvantages are that the powder is more expensive to produce and the molder needs to keep good control over stocks of the required colors.

An alternative is to *dry blend* the pigment with the powder. Some preliminary mixing may take place outside the mold and the natural tumbling action that occurs during rotational molding ensures good mixing in the mold. This is an attractive option to molders because they need to purchase only unpigmented material and this facilitates economies of scale and removes the need for tight stock controls on different colors. The disadvantage is that the pigment is not homogenized with the polymer nearly so well as in compounding using the extruder. As a result, the properties of the end product are not so

good and are very sensitive to the amount of pigment used. As the pigment is not intimately bound to the polymer, it can also leave deposits on the mold called plate-out or staining.

To improve the dry blending of pigments into polymers, *high speed mixers* or *turbo blenders* can be used. These combine the pigment and the polymer at modestly high temperatures in a paddle-type mixer. The powdered pigment particles become bonded or fused to the softened surface of the plastic particles and the resulting material can be rotomolded in the normal way. The output from the high speed mixer is very clean to handle and does not transfer the pigment to the mold. The properties of the resulting molding are still not as good as from compounded material but material handling is much cleaner.

The vast majority of the pigments used in rotational molding are in powder form, but in recent years the use of liquid pigments is becoming popular. These can be economic and potentially offer the convenience of dry mixing with the properties of compounded material. However, in most cases the formulations still have to be perfected for rotational molding. The following sections discuss the different coloring methods in more detail.

3.10.1 *Dry Blending*

Dry blending is the most popular way of coloring rotational molding grade powders. It is attractive because cost savings can be made by purchasing bulk quantities of natural material and coloring this as required prior to molding. There are many methods of blending powders including low-intensity, inhomogeneous mills such as the ribbon blender and paddle mixer and high-intensity mills such as the Henschel mixer. The effectiveness of blending depends on many factors, such as particle size distributions, bulk density, the true densities of the ingredients, particle shapes, surface characteristics, flow characteristics such as angle of repose and dry flow rate of each of the ingredients, friability, state of agglomeration, moisture content, and temperature. The tip speed of the blender paddles can also be important, particularly with liquid pigments.

One of the most common dry blenders is the low-intensity cross-flow or Vee mixer (Figure 3.20). The double-cone mixer with internal baffles is also quite popular (Figure 3.21). Double-ribbon blenders are used for very large batches. Most rotational molding grade powders are relatively easy to tumble-blend, although large fractions of fines can lead to fluidization. Most other types of additives such as dispersants, flow enhancers, antistatic agents, and

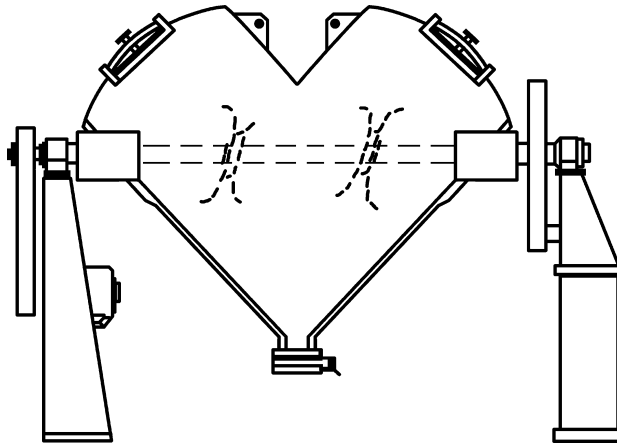


Figure 3.20 Vee mixer

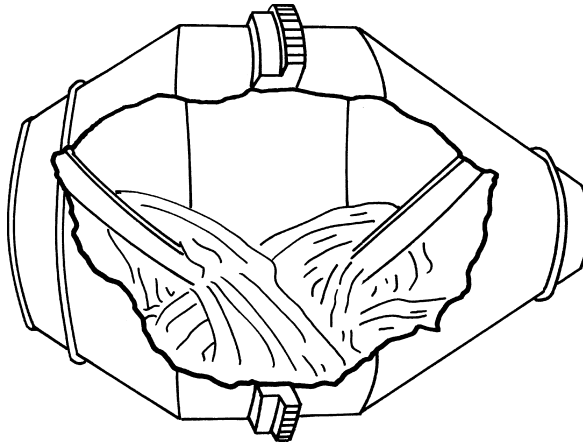


Figure 3.21 Cone mixer with internal baffles

fillers, are relatively easy to tumble-blend. Other additives, such as UV modifiers, impact modifiers, thermal stabilizers, and antioxidants such as vitamin E, should be melt-blended with the polymer prior to pulverization. Some additives, such as UV modifiers and impact modifiers can be dry-blended but require 2 to 5 times higher dosage than melt-blended additives to achieve the same effectiveness. Low-intensity mixing requires long tumbling times of 30 min or more, depending on the polymer and adduct particle characteristics. Vee mixing, ribbon blenders, and double-cone mixers are more efficient mixers and so minimum blending times of 15 min or so are recommended.

Probably the most effective dry blending mill is the high-intensity Henschel-type mixer. Blending times of 1 to 5 minutes are sufficient with the blend exiting the mixer on blend temperature, not time. It appears that the mechanism for dispersion focuses on frictional heating of the powder particle during the tumbling process, to a point where the polymer is tacky and the pigment sticks to it. Excessive frictional heating in the blender leads to agglomeration of the powder into cake or clumps, or to the point where thermal degradation and outgassing can occur.

3.10.2 *High Speed Mixing (Turbo Blending)*

As well as the low speed tumble mixing referred to above, high speed turbo blending can also be used to induce more frictional heating and encourage better mixing of the pigment and the plastic powder. In this case, the pigment adheres to the tacky surface of the plastic powder, providing a relatively "clean" material that does not leave traces of pigment on the mold. However, as there is little or no shearing during rotational molding, there is a basic problem with dry blended or turbo-blended pigment/powder because the pigment tends to be trapped at the boundary of the individual powder particles. If the pigment has a nucleating effect on the structure of the plastic, this causes polymer morphological features that may have a major effect on the mechanical

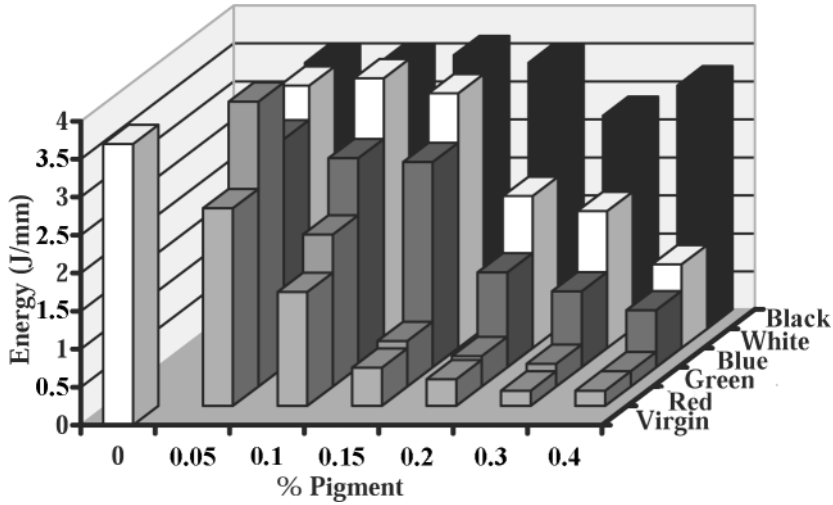


Figure 3.22 Effect of pigmentation level on impact strength of rotationally molded polyethylene, redrawn, used with permission of copyright owner[26]

properties. If a nucleating pigment is turbo blended, the amount of pigment has little effect on the tensile strength, but the strain at break (and hence the toughness) decreases dramatically as the pigment level increases above about 0.05%.[27] The pigment level at which impact properties start to decrease depends on the type of pigment.[28] The results of tests on pigments that were turbo-blended are shown in Figure 3.22. The data is for illustration only and should not be taken as being indicative of the effects of these colors under all circumstances.

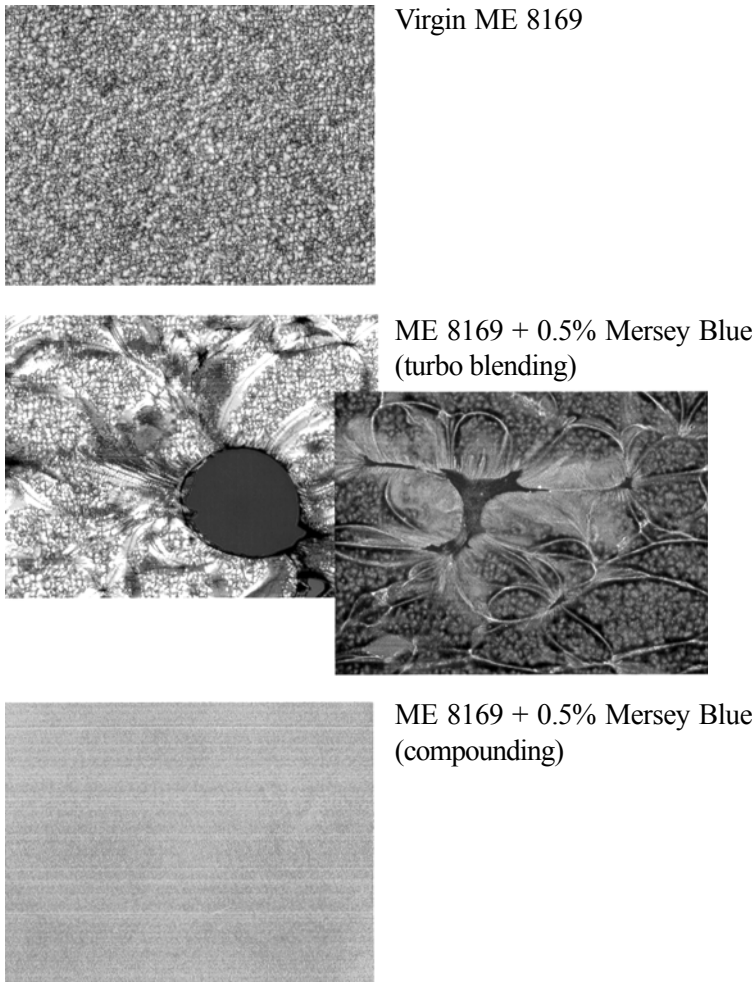


Figure 3.23 Microstructure of rotationally molded polyethylene parts with blue pigment. Reproduced with permission of Borealis AS, Norway

3.10.3 *Compounding*

If the production volume warrants, all colorants should be melt-blended with the polymer prior to grinding, because this gives the best mechanical properties in the molded part. Also, if the pigment concentration must be in excess of 0.2% (wt), for opacification or color intensity, it must be melt-blended with the polymer. This is because melt compounding provides the best blending and homogenization of the pigment and the plastic. Figure 3.23 illustrates the structure of rotomolded articles manufactured from compounded powder and high-speed blended material. The base resin and pigment was the same in both cases. Several interesting aspects are shown. The compounded material has a very uniform structure that is much finer than the structure seen in the unpigmented material. In contrast, the dry blended material has a very coarse and nonuniform structure. It is also apparent that the latter material has some unusual structural formations at the boundaries of the particles. This leads to embrittlement of the molded part.

Experimental investigations of the rotational molding of polyethylene with various types and amounts of pigments have shown that if the powder is subjected to thermo-mechanical action prior to molding, there is a marked decrease of the size of the crystalline texture or morphology of the rotationally molded product and the mechanical properties of the end product are improved.[26]

3.10.4 *Types of Pigments*

There are about 200 pigments available to the plastics processing industry, but only about 30 of these are suitable for rotational molding.[29-31] The long time at elevated temperature eliminates many organic pigments. Since many rotationally molded parts are used outdoors, the UV resistance must be high, and this eliminates some other pigments. For the higher temperature engineering resins, such as nylon and polycarbonate, the pigment palette is very restricted and most of the important colors must be melt-blended. Less than 20% of all the colorant recipes used in polymers will work in dry-blended rotational molding. The primary reason is that there is no melt shear mixing either in the blending or the rotational molding process.

There are several classes of pigments. Pigments containing heavy metals, such as lead, cadmium, and chromium, yield very intense colors and are relatively inexpensive but are restricted. They cannot be used in toys, FDA products,

sporting goods, or recreational equipment. Other inorganic pigments based on tin, iron, and zinc are not restricted but do not have bright colors. Cadmium pigments are historically one of the most widely used pigment groups used in rotational molding. Their heat stability and outdoor light stability are excellent. They offer a broad range of very clean and bright colors and they can be used at levels that do not affect the impact properties of the resin. They are relatively inexpensive, easy to disperse, do not bleed, and have good opacity. Also, they do not interfere with the crosslinking process in XLPE.

The major drawbacks for these pigments are the regulatory restrictions placed upon them by various governing bodies. The cadmium in these pigments will not be absorbed into the human body if ingested or inhaled. Unfortunately, there are cadmium compounds that can be absorbed by the human body and some of these are quite toxic. As a result, the cadmium pigments are guilty by association and, thus are heavily regulated.[32] This is also true for lead pigments. Since in most cases these pigments cannot be used, and since there are no other inorganic pigments that will give the bright yellows, oranges, and reds that are very popular, molders are forced to look to the organic pigments for help.

Organic pigments fall into two primary categories: azo type pigments and polycyclic pigments. The majority of all organic pigments (>65%) are the azo type pigments and their color range follows very closely to that of the cadmiums, mainly yellow to red. The polycyclic pigments consist of almost everything else with the quinacridones (red and magenta) and the phthalocyanines (blue and green) being the most important for rotational molding. Carbon black is also an important organic pigment but does not fall into either category.[33]

In general, organic pigments are strong, bright, clean, and translucent with reasonable heat and outdoor light stability. However, they are difficult to disperse, they are expensive and they can shift in color over a range of processing temperatures. Some cause warpage problems, some will bleed, and because of their small particle size, static problems become more apparent. Organic pigments are more reactive than inorganic pigments. This is especially noticeable with crosslinking materials where the peroxide can react with certain pigments causing a large shift in color. Crosslinked polyethylene is inherently yellow from the crosslinking agent. Ultramarine pigment is particularly sensitive to this problem, in that the reaction with the peroxide yields a yellow-green color.

Fluorescent additives are very expensive and tend to fade. As a result, they are used with inorganic pigments to minimize the fading effect. Fluorescents have very high static charges and will migrate during rotation in the oven to yield nonuniform coloration. Many pigments are polymer-specific. For example, due to its higher crystallinity, natural (or unpigmented) HDPE has a higher opacity than LLDPE. Titanium dioxide (TiO_2) is a standard opacifier.

Some polyethylenes are very thermally sensitive and so color must be overcorrected to allow for yellowing during processing. A high fraction of fines can reduce opacity and color intensity, but fines do not heat sufficiently to allow uniform dispersion of the additive. Improper particle size distribution is frequently the cause of striations, streaking, and swirling in pigmented powders. All fine powders adsorb moisture and many pigment powders absorb moisture. When the pigment is to be tumble-blended with the polymer, it must be thoroughly dried, then kept very dry until charged into the mold.

Plate-out, or the tenacious adhesion of pigment and polymer on the inner mold surface, is considered to be the most vexing problem when working with dry blended pigments. Certain aspects of plate-out were discussed earlier. The condition of the mold surface is, of course, most critical. One way of minimizing the effect is to use a baked-on, professionally applied permanent or semipermanent mold release such as FEP fluoropolymer or siloxane. Discussion of these mold releases is covered elsewhere.

Other problems deal with discoloration or color shift during processing. It is recommended that for most pigments, including TiO_2 and carbon black, the oven temperature must be reduced and the time in the oven increased. Streaking is more apparent with glossy molds and glossy surfaced parts than with matte finished molds and parts.

For PVC plastisols, the pigments must always be milled. Engineering polymers such as polycarbonate require melt-blending of all additives, including pigments.

Rotationally molded parts can have special effects such as granite, marble, and sparkle. Mixtures of different sized melt-blended powders yield the best results. For sparkle, metallized PET flake is recommended. Metal flake such as coated aluminum should not be used, since it may oxidize explosively in the oven. Low concentrations of mica, at 5% to 15% or so, will also yield a sparkle surface. Photochromic and thermochromic effects can be achieved with certain pigments but at a very high cost. Pearlescents are somewhat successful

but the dosage must be low to minimize impact property loss. The preferred way of achieving a look of high pearlescence is to increase the wall thickness. Representative pigment types are given in Table 3.9.

Table 3.9 Types of Pigment

Organic Pigments (Complex chemicals)
Green and blue phthalocyanines
Red, yellow, and orange azos
Purple and violet quinacridones
Carbon black
Inorganic Pigments
Red, yellow, and orange cadmiums (HM)
Yellow and orange chromes (HM)
Titanium dioxide white
Brown and black iron oxides
Ultramarine blue sodium silicates
Blue cobalt (HM)
Ochre, yellow, and brown titanates

3.10.5 *Aesthetics of Rotationally Molded Parts*

As with most molded products, the aesthetics of rotationally molded parts are very important.[34] Many rotationally molded parts have a high public profile and so not only is color important but the overall appearance can affect the success or failure of the product. With materials such as nylon it is relatively easy to achieve an excellent finish using paint. Examples of painted rotationally molded parts are given in Chapter 7. Even with the polyethylenes, painting is possible if the surface of the molded part is treated. In order to improve the adhesive properties of polyethylene it is necessary to increase the surface roughness of the material or its surface tension. This can be achieved by using a variety of methods, such as flame treatment, fluorination, etching with acid, corona treatment, plasma treatment, or UV treatment. Recent new technologies[24, 25] involve plasma treatment of the plastic powder, which then produces a rotomolded molded part that requires no further treatment prior to painting.

Plasmas are created by the application of power to a gas.[35] A variety of systems can be used, but the basic principle relies on the interaction between charged particles of plasma (electrons, ions, neutrals, metastable species, and photons) and the material surface. Energized particles are formed by means of

repeated interactions between electrons and atoms or molecules. The effects of the interaction between polymeric surface and cold plasma can be of three types: ablation, crosslinking, and superficial activation. Depending on the gas used and the nature of the polymeric material, one of these three phenomena will dominate.

The rotational molding industry is also fortunate in that there are some excellent methods of adding permanent graphics to the end product. Specially developed molded-in graphics and postmolding graphics[36] can be used very effectively as shown in Figure 3.24.

Figure 3.24 Example of molded-in graphics on rotationally molded part, courtesy of Mold-in Graphics Inc.

3.10.6 *Other Types of Additives*

There are several types of common additives that may cause processing problems in rotational molding. Antistats are usually added to reduce static charge build-up and are useful only during the servicing of the mold, prior to heating. The maximum dosage should be 2 to 3 ppm, and the standard antistat should

be an animal or vegetable fat. High concentrations of antistats lead to pigment migration and plate-out. Static dissipation on the machine arm, spider, and molds usually occurs in the water cooling step of the process. When rotational molders use air cooling only, the static charge can exist until the mold and spider are grounded at the service station. Adding additional antistat to minimize static charge usually leads to substantial pigment plate-out.

Stearates are sometimes recommended as internal mold releases since they bloom to the interface between the mold and the formed part. However, many common stearates outgas to produce porosity on the part surface. Permanent mold releases are preferred over stearates.

Other additives are colorants as well. For example there are four types of UV additives: *UV absorbers*, *UV attractors*, *UV quenchers*, and *UV scavengers*. UV absorbers are pigments such as carbon black. Carbon black dosage of 2% is considered sufficient UV protection for all but the subtropics and tropics (see Figure 3.25). Concentrations of 7% (wt) or more are required for tropical climates. Other absorbers include the hydroxybenzophenones and hydroxyphenyl-benzotriazoles.

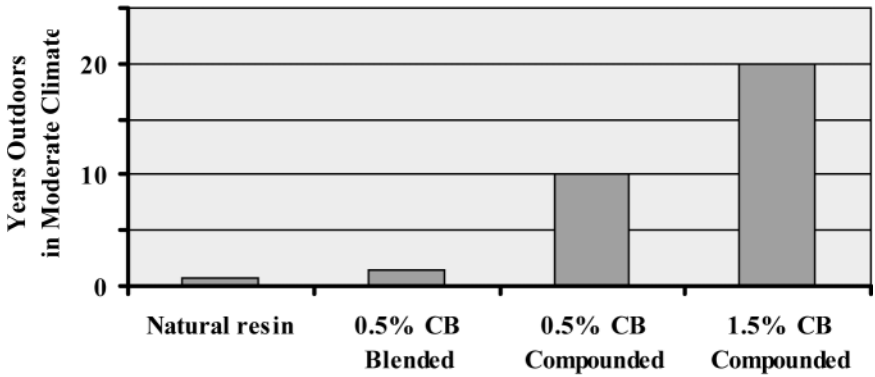


Figure 3.25 Effectiveness of carbon black (CB) in polyethylene, redrawn, used with permission of copyright owner

UV attractors are organics such as blue and green phthalocyanines. Care must be taken when using phthalos since excessive levels may lead to warpage, shrinkage, rub-off, odor, and poor opacity. UV quenchers deactivate and dissipate UV energy as absorbed heat. Nickel salts are UV quenchers. UV scavengers take up free radicals from damaged polymers. Hindered amine light stabilizers (or HALS) are scavengers. HALS are

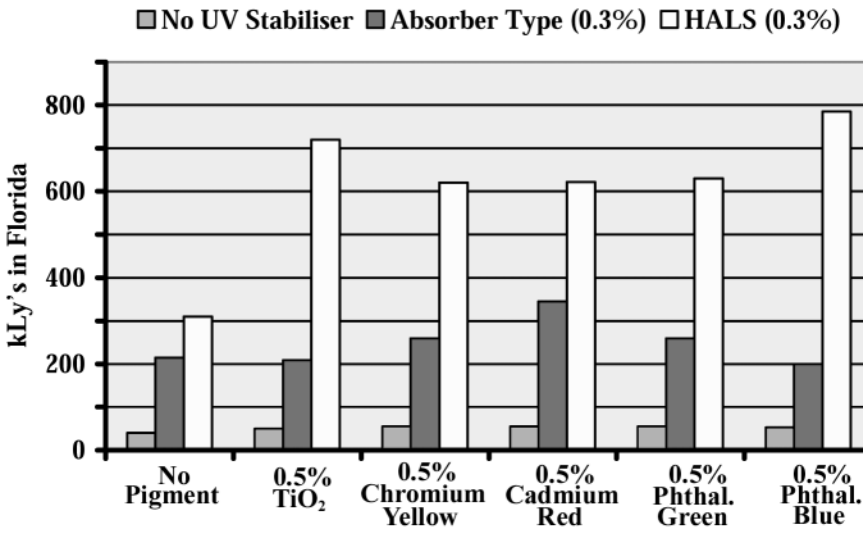


Figure 3.26 Comparison of UV absorbers for various pigments (samples 2 mm thick, data to 50% retained tensile strength), redrawn, used with permission of copyright owner

much more effective than carbon black as UV absorbers (see Figure 3.26), but are considerably more expensive. As with all organic additives, care must be taken to prevent degradation and reduction in the effectiveness of HALS during the heating portion of the rotational molding process. HALS are most effective when low oven temperatures and long oven times are used. For engineering polymers requiring higher oven temperatures, the effectiveness of HALS must be determined with accelerated UV tests before the products are approved for outdoor or even long-term indoor fluorescent use. From a UV viewpoint, black pigment is the best UV barrier and red and yellow are the worst. The opacifier TiO_2 is the best white pigment, providing UV resistance and opacification for most olefins at about 5% or so.

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4 ROTATIONAL MOLDING MACHINES

4.0 Introduction

The basic principle of rotational molding involves heating plastic inside a hollow shell-like mold, which is rotated so that the melted plastic forms a coating on the inside surface of the mold. The rotating mold is then cooled so that the plastic solidifies to the desired shape and the molded part is removed. There are many methods that can be used to achieve the essential requirements of mold rotation, heating, and cooling. It has been estimated that about 40% of the rotational molding machines in use in the U.S. are home-built. Of the remaining 60%, about 70% are more than ten years old, and 40% are more than twenty years old. The percentage of home-built machines is even higher in some other parts of the world, but there is a move toward the purchase of new machines as molders start to concentrate on their core business in order to survive in very competitive markets. The data acquisition systems and process control on commercial machines also make them attractive and compare very favorably with what is available in competing technologies such as blow molding, thermoforming, and injection molding.

Most people with general engineering skills tend to take the view that a rotational molding machine is not a complex piece of equipment. While few individuals or molding companies would contemplate building a blow molding machine or an injection molding machine, there has been no such reluctance to build rotational molding machines. This has worked well for some small companies in that it has allowed them to meet internal needs or satisfy a local niche market, but this do-it-yourself approach has also harmed the image of the industry. Home-built machines by their nature often do not have much investment in safety features or aesthetics and are highly individual in appearance and performance.

The build vs. buy strategy depends on many circumstances and quite often relates to the nature of the business and the local market. The uniqueness of the part can dictate this decision. A company may be in an engineering business not directly involved in plastics, but it currently purchases hollow plastic parts. It may take a business decision to manufacture these in-house. From its general engineering expertise such a company can be quite capable of making a simple machine to rotate, heat, and cool a mold for making the

parts. The machine will be product specific but will be as good or better than anything that the company could buy for its needs, and will certainly be less expensive.

Another common scenario is where a company manufactures products from fiber-reinforced plastic (FRP) and/or thermoformed plastic, but desires to broaden its product range. Rotational molding is a closely allied manufacturing method and from the company's expertise in working with plastics, it is no great challenge for it to make a rotational molding machine for new products that are similar to its existing lines, in order to broaden its customer base. There are also many examples of individuals or companies that use tanks or containers for dispensing or storing insecticides and chemicals, and they decide to manufacture their own storage containers because these are regarded as being too expensive or have limited availability. Or there may be confidentiality associated with the product. If the part being rotationally molded requires special polymers, special treatment, or special processing conditions, the logical business decision may be to construct a special machine specifically for that particular part.

In circumstances such as those described above, it may well have proved advantageous to build rotational molding equipment in-house. The trend in the industry is, however, toward high technology with more sophisticated molds, improved machine controls, internal cooling, and mold pressurization. Commercial machines will undoubtedly offer economic advantages in terms of faster cycle times and more economic operation, so that it will be difficult for molders to remain in competitive market sectors without having this type of equipment.

Full details on the types of machines used by rotational molders are given in other sources.[1–3] In this book the emphasis is on the concepts and principles of rotational molding and so this chapter gives an overview of the types of machines that are available, and concentrates on the technology of the equipment.

4.1 Types of Rotational Molding Machines

Since rotationally molded parts range in volume from 0.05 liters to more than 10,000 liters, generalization on machine types is difficult. The common aspects of the process are that the mold and its contents need to be rotated, heated, and cooled. There also needs to be a convenient opportunity

to remove the end product from the mold and put a fresh charge of plastic into the mold. Furthermore, while the servicing station is always required, not all machines need ovens or cooling stations. If a reactive liquid such as epoxy or catalyzed unsaturated polyester resin is used as the polymer, formation of the monolithic structure occurs without external heat and the shape of the end product is retained without the need for cooling. Furthermore, in some instances, the heating cycle is so long that cooling can be achieved simply by allowing the mold to rotate in quiescent room air.

Nevertheless, there are some basic types of commercial rotational molding machines that are common across the industry. The varieties of machines that are available are described below.

4.1.1 *Rock-and-Roll Machines*

This design concept of a rocking action about one axis ("rock") and a full 360° rotation about a perpendicular axis ("roll") was one of the earliest used for rotational molding. This type of machine is shown as a schematic in Figure 4.1.[4] It has been generally accepted that machines that are capable of providing full 360° rotation about two perpendicular axes have superseded the "rock-and-roll" concept. For a long time it has been thought that rock-and-roll machines are best suited to end products that are approximately symmetrical about a central axis, such as lamp-posts, canoes, and kayaks. However, in recent years there has been a renewed interest in rock-and-roll machines because they offer simplicity in design and have the major advantage that it is easier to get services to and from the mold. It has also been found that the control over the wall thickness distribution can be just as good as that achieved on a biaxial rotation machine, for the vast majority of mold shapes.

In a rock-and-roll machine, usually a single mold is mounted in the mold frame, the rotational speed is low (typically 4 rev/min), and the rocking angle is less than 45°. Direct gas impingement is an effective method of heating for sheet-metal molds and is often used in rock-and-roll machines. If the gas jets are played against the bottom or lower portion of the mold assembly, a simple sheet-metal shroud over the top portion of the mold assembly is sufficient to carry away combustion products. The proximity of the gas jets to the metal mold is an important factor in mold heating. The gas jets should always be a fixed distance from the outside surface of the mold to avoid hot spots. Obviously this is easiest to achieve in cylindrical molds.

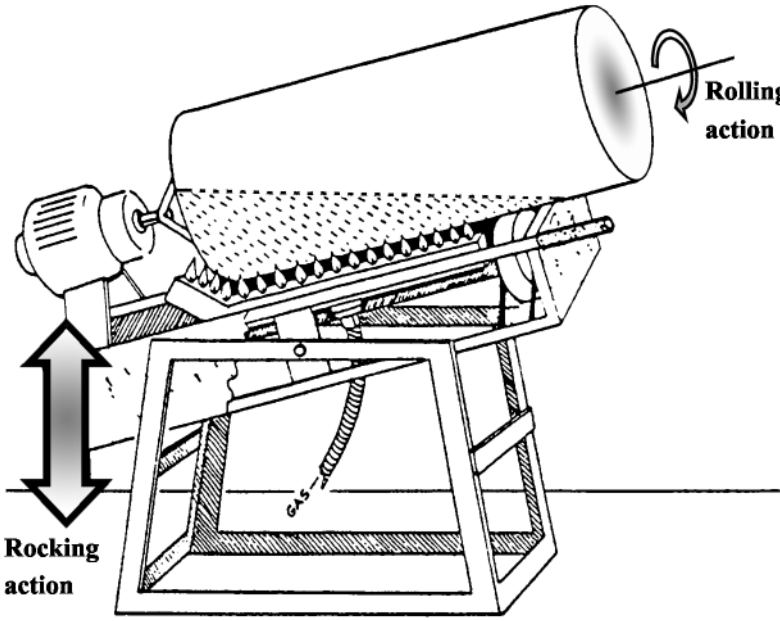


Figure 4.1 Typical rock-and-roll machine, used with permission of The Queen's University, Belfast

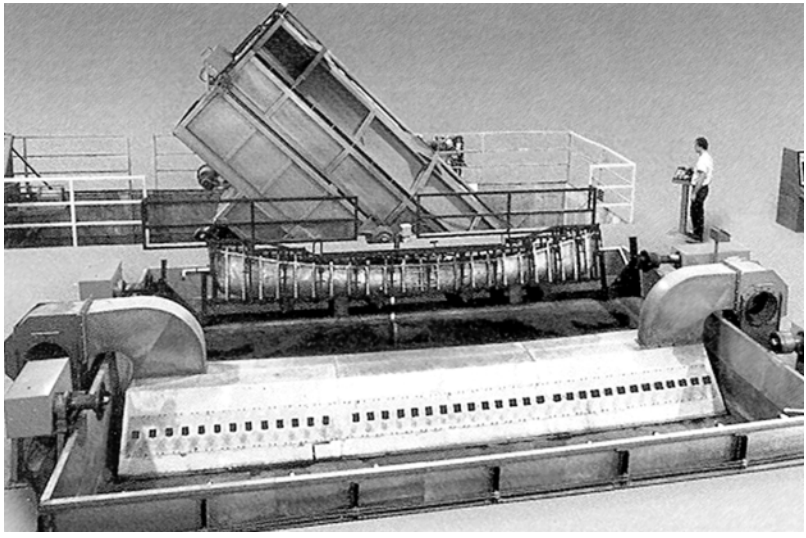


Figure 4.2 Rocking oven type of rotational molding machine. Cooling and servicing areas are in the foreground, courtesy of Ferry Industries, Stow, Ohio

In the *rocking oven machine* the mold is surrounded by an oven, heated by hot air, and the oven rocks with the mold as shown in Figure 4.2. The rocking oven must contain appropriate burner assemblies, ducting and blowers, as well as an adequate shroud. In some cases the mold assembly is mounted on a rail carriage, so that it can be rolled from the oven chamber to the cooling area. Frequently the cooling area is also the servicing station. For smaller rock-and-roll machines, the oven can be shuttled, or crane-lifted, over the mold assembly. For larger machines, the oven is stationary and the mold assembly is moved into it through a single door. Commercial rotational molding machinery builders do manufacture rock-and-roll machines, but most rock-and-roll machines are home-built.

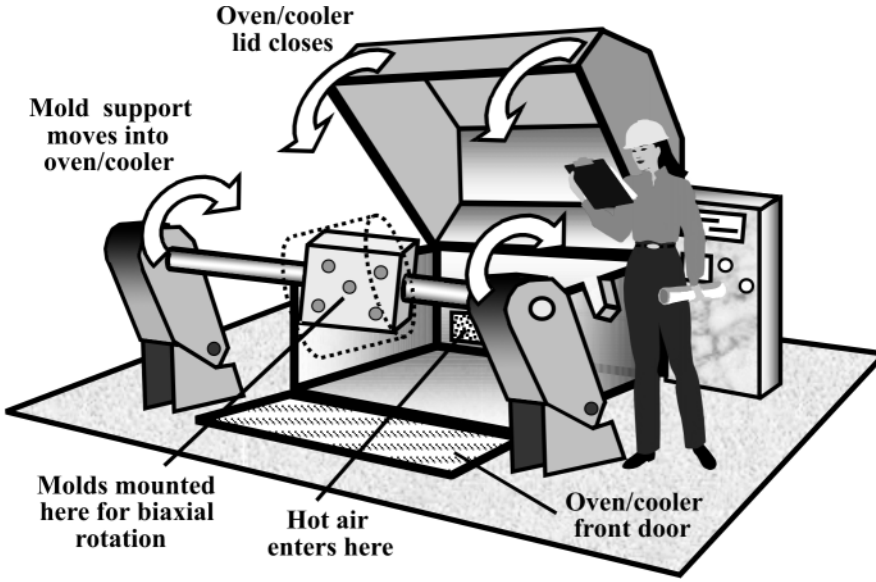

Oven/cooler lid closes
Mold support moves into oven/cooler
Molds mounted here for biaxial rotation
Hot air enters here
Oven/cooler front door

Figure 4.3 Clamshell type rotational molding machine

4.1.2 *Clamshell Machines*

This machine is characterized by an oven that closes in a "clamshell" action over the mold as shown in Figure 4.3. These machines have the attraction of a small floor footprint. The machine provides full biaxial rotation and has the advantage that the horizontal shaft can be supported at both ends. The molds are located on assemblies that are in turn mounted on turntables geared through the main shaft/axle. When the oven door is closed, the main axle rotates, turning the molds in a Ferris-wheel fashion and through gearing, the turntables rotate the molds about their axes.

Heated air is circulated through the cabinet until the appropriate polymer temperature is achieved, then cooling occurs by cooled air and/or water mist. At the completion of the cooling cycle, the cabinet door opens with a book action, the molds are opened, and the parts are removed. The molds are then cleaned, inspected, and refilled with polymer and the next cycle begins. In some designs of clamshell machines, the molds leave the oven chamber at the end of the heating phase so that cooling can take place externally. This makes the oven chamber free to receive another set of molds while the previous set are being cooled and serviced.

4.1.3 *Vertical Machines*

In this novel type of machine design there is a central horizontal axis and the molds are on arms that radiate out as shown in Figure 4.4. At appropriate times, the central axis indexes the molds through 120° so that they move into the oven, the cooling area, and the service zone in sequence. The advantages of this design are that high volume production of small parts is possible in a small floor space.

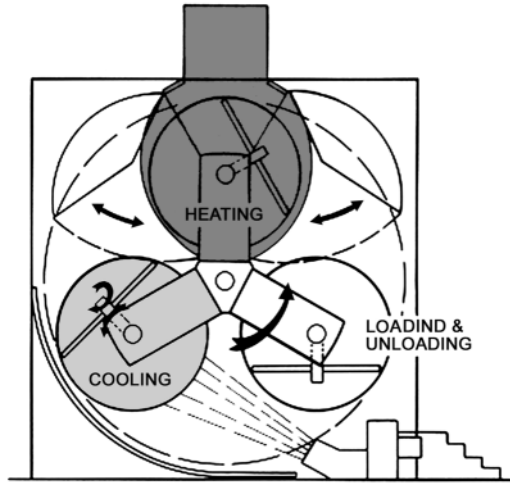


Figure 4.4 Side view of vertical type rotational molding machine, courtesy of Ferry Industries, Stow, Ohio

4.1.4 *Shuttle Machines*

Shuttle machines were developed as an attempt to conserve floor space. There are many types of shuttle machine designs. In one type of machine,

the mold assembly, mounted on a rail carriage, is shuttled from the servicing/cooling station to the oven station, and back again to the servicing/cooling station, as shown in Figure 4.5. The efficiency of the shuttle machine is improved by using a dual-carriage design, whereby the oven is always occupied by the heating of a mold while the mold on the other carriage is being cooled/serviced. If the cooling/servicing time for the mold equals the heating time, then this system can approach the optimum in terms of maximum output rates. The key to longevity of this machine is the protection of the drive engine from the high oven temperatures and the corrosiveness of the cooling water. Since the scheduling of time in the oven is at the discretion of the operator, the dual-carriage machine is more versatile than the fixed-arm carousel or rotary machine discussed below.

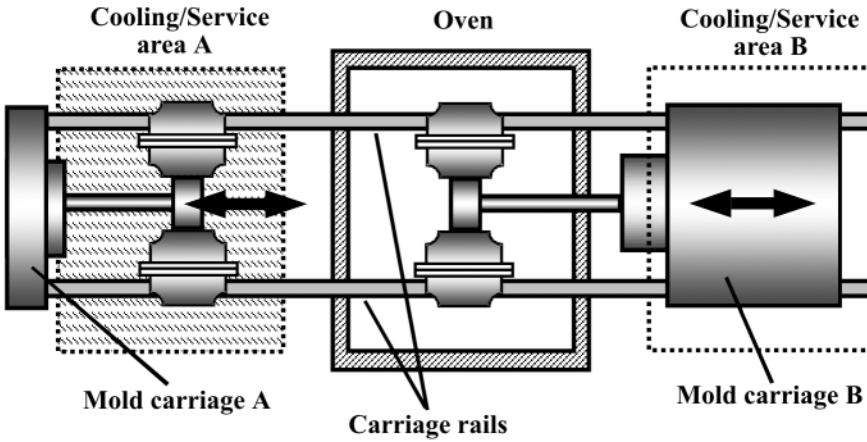


Figure 4.5 Shuttle type rotational molding machine, showing mold set B in oven and mold set A in cooling and service area

4.1.5 *Fixed-Arm Carousel Machine*

The carousel, turret, or rotary machine was developed for long production runs of medium to moderately large parts. It is now one of the most common types of machine in the industry. The earliest machines had three arms 120° apart that were driven from a single turret. All arms rotate together on fixed-arm machines. One arm is at each of the three stations — heating, cooling, servicing — at all times, as shown in Figure 4.6. The carousel machine exemplifies the advantages of the rotational molding process in that different molds, and perhaps different materials can be run on each arm. It is possible to change the combinations of molds on one

arm or on the other arms at regular intervals so that there is great versatility in production schedules. A disadvantage of the fixed-arm machines is that for optimum use, heating, cooling, and servicing times have to be matched. If they are not, then the cycle time is dictated by the slowest event and time is wasted in the other areas. This disadvantage has been overcome to some extent with the development of the independent arm carousel machine discussed in Section 4.1.6.

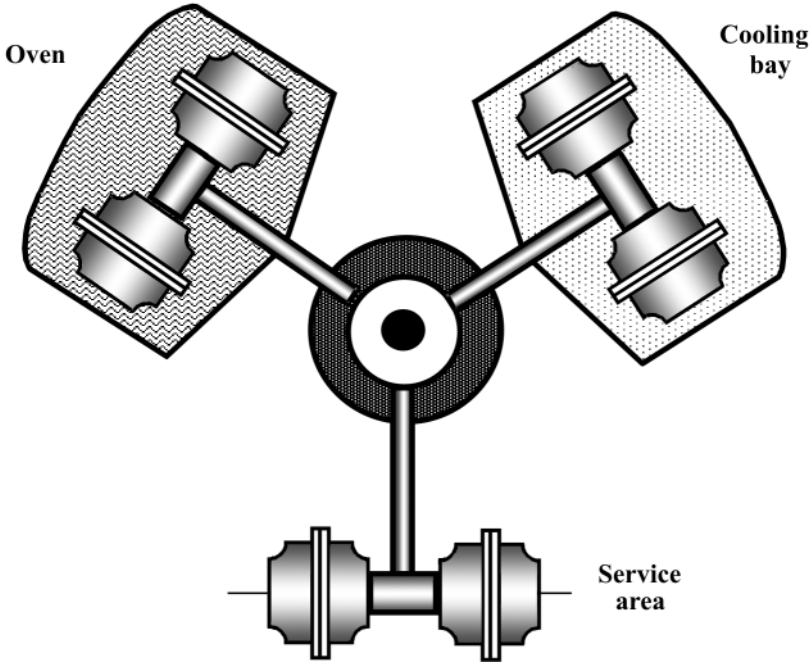


Figure 4.6 Fixed-arm carousel machine, used with permission of The Queen's University, Belfast

Four-arm fixed-arm machines, with the arms 90° apart, are also available. Usually the fourth arm resides in an auxiliary cooling station when the other three are in heating, cooling, and servicing stations. As a result, four-arm machines are popular when the process is controlled by the cooling cycle.

4.1.6 *Independent-Arm Machine*

Recently, independent-arm machines have been developed in an effort to improve the versatility of rotary machines. The current machines have five designated stations, and can have two, three, or four arms that sequence

independently of one another. The first key to versatility is having fewer arms than stations. This allows the operator to designate the "empty" stations as auxiliary oven stations, auxiliary cooling stations, and/or to separate the loading and unloading steps in the servicing stations. Figure 4.7 shows one configuration, a four-arm machine with an auxiliary cooling station. Although these machines are more expensive than the other machine designs discussed above, they are ideal for custom rotational molding operations and now dominate the market for new machine sales.

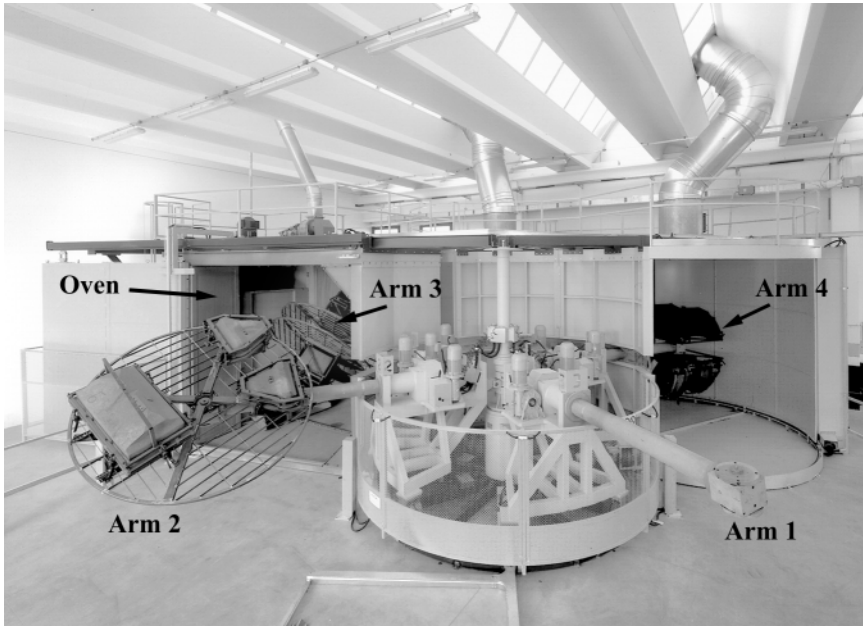


Figure 4.7 Independent-arm rotational molding machine, courtesy of Polivinil, Italy

4.1.7 *Oil Jacketed Machines*

Direct heating of a mold with liquid is much more efficient than heating by air in an oven. It is not surprising therefore that the heating of molds by circulating a fluid in a jacket surrounding the mold has been attempted and is being used commercially in a small number of specialized application areas. It is particularly attractive where the material has to be heated to high temperatures. For example, with polycarbonate, mold temperatures over 300°C (572°F) are needed and heated oil jacketed molds have been found to be very successful with this material.

The disadvantage of such systems is that it is difficult to avoid oil leaks in the rotating joints. When this happens there are unpleasant fumes and the plastic can become contaminated. To alleviate such problems, heated salts have been used in the jacketed mold. However, such machines are rarely used commercially.

In recent years, there has been a renewed interest in direct mold heating because not only is the liquid heating very efficient, but the absence of an oven means that it is easy to get process control devices close to the mold without worrying about overheating of sensitive electrical equipment.

4.1.8 *Electrically Heated Machines*

One of the most innovative types of rotational molding machine to have emerged in recent years is an electrically heated system in which a network of fine electrical wires are embedded in a cast, nonmetallic mold.[5–7] The machine, illustrated in Figure 4.8, provides full biaxial rotation and the power supply to the heating elements is by means of slip rings in the rotating joints. Cooling is provided by blowing air through channels that are cast into the mold, as shown in Figure 4.9. This machine concept has the advantage of direct heating of the mold and so it is very energy efficient. It is claimed that up 80% of the energy being input to the system is used to melt the plastic, compared with about 10% to 40% on a hot air oven machine. As the electrical machine does not use an oven, it also facilitates

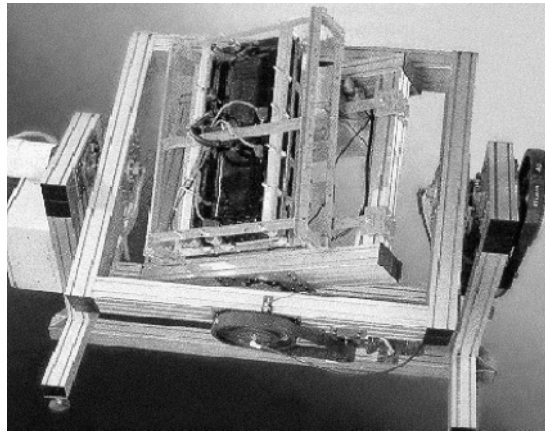


Figure 4.8 Ovenless rotational molding machine, electrically heated composite molds, courtesy of Wytkin Industries, Croma, Illinois

easy access to the mold for instrumentation, extra charges of material, etc. The disadvantages are that the molds cannot easily be modified and cycle times are long since heating, cooling, and servicing take place sequentially rather than in parallel as in shuttle or carousel machines.

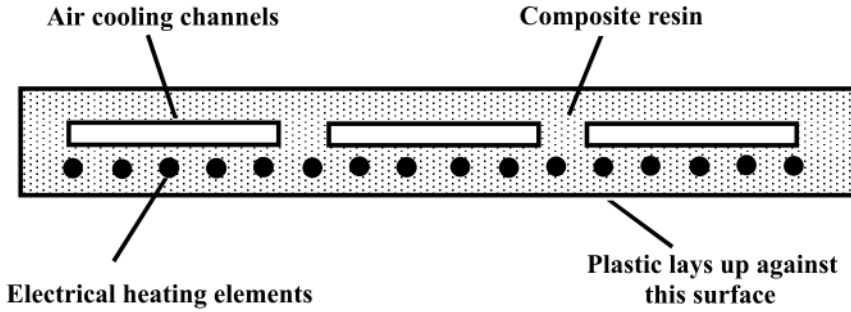


Figure 4.9 Section through wall of electrically heated mold, used with permission of The Queen's University, Belfast

The carrier material is a composite of a thermosetting resin with fillers/additives to assist mold strength, thermal conductivity, etc. A mold release agent can be incorporated into the composite resin and this helps with the consistency of the molding process.

4.1.9 *Other Types of Machines*

Other types of mold heating involving microwaves, induction heating, and infrared heating have been developed but are not in widespread use commercially. Infrared machines have been shown to be very thermally efficient in a rocking oven type of machine design. The problem with these types of machine is that it is difficult to provide uniform heat to all areas of the mold. If the mold wall varies in thickness, as it often does in cast molds and in the flange regions, then these areas will affect the heat input from induction coils, for example. In other cases, with infrared heating for example, the proximity of the heat source to the mold influences the temperature, and support frames, brackets, spiders, and machine arms can shadow the mold from the heating elements.

Nonmetallic molds, for example glass fiber reinforced plastic molds, have been used for prototype work and small-scale production. These molds are heated in the oven like metal molds. They have the advantage of very short lead times, if a pattern or part that can be copied is available. The disadvantage is that the glass fiber does not have a good thermal

conductivity and suffers embrittlement at elevated oven temperatures.

4.2 Machine Design Considerations

A common feature of rotational molding machines is that a mold is rotated, usually about two perpendicular axes. Figure 4.10 illustrates a variety of ways in which the rotation is achieved on commercial machines. The largest mold is accommodated on the *offset arm*, or a variety of molds can be placed on the plate. In the *straight arm* design, a greater number of smaller molds can be used. On the straight arm, the rotational motion of each mold is slightly different to the straight arm, since the centre of gravity of the mold must always be displaced from the point of coincidence of the two axes of rotation. On modern commercial rotational molding machines there is normally one, two, or three hollow channels passing through the arm of the machine. These allow access of gases to/from the molds, if required.

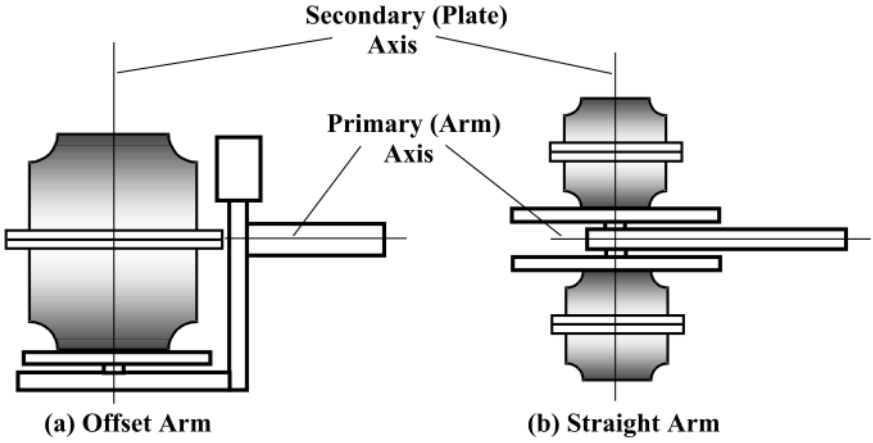


Figure 4.10 Two types of mold support arms, used with permission of The Queen's University, Belfast

A number of specific machine design parameters are now considered.

4.2.1 *Mold Swing*

The size or capacity of a commercial rotational molding machine is specified in terms of two parameters. The first is the *maximum weight of the mold* or molds that can be placed on the arm. The other parameter is the

mold swing. This effectively defines the limits on the size of mold that will fit on a particular machine. It is linked to the size and shape of the space inside the oven and cooler. In their specification sheets, machine manufacturers provide an envelope inside which the mold must fit to ensure that it does not come into contact with the oven or cooler as it rotates. Figure 4.11(a) illustrates the mold swing for an offset arm machine and Figure 4.11(b) illustrates the mold swing dimensions for a straight arm machine. To assess whether or not a mold will fit on a particular machine it is necessary to check if the mold height and longest diagonal dimension will fit inside the dotted lines. This is illustrated in the following Example.

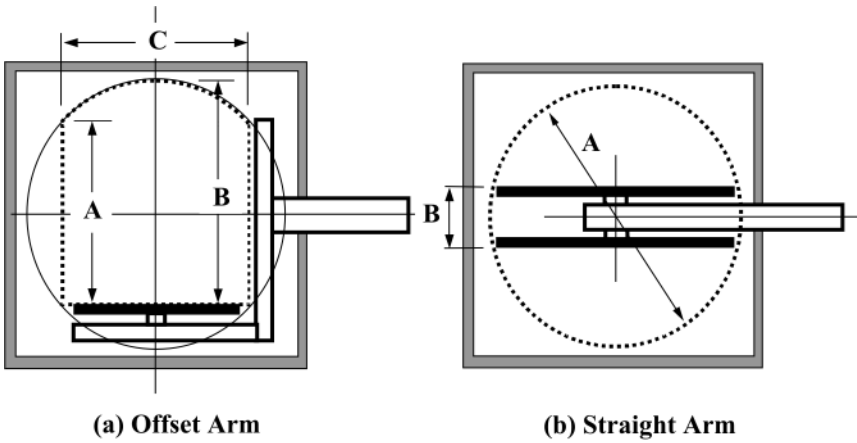


Figure 4.11 Mold swing dimensions for offset and straight arms, used with permission of The Queen's University, Belfast

Example 4.1

A rotational molding machine has both offset and straight arms. Referring to Figure 4.11, the mold swing for each is as follows:

(a) Offset arm	(b) Straight arm
A = 1435 mm	A = 2415 mm
B = 1917 mm	B = 280 mm
C = 1930 mm	

What is the largest cube shaped mold that could fit on each arm?

Solution

(a) For the offset arm, the first step is to check if the maximum diagonal for the cube can be 1930 mm (dimension C). From Pythagoras's theorem the side of the cube will be given by

$$\text{side} = \sqrt{0.5 \times (\text{diagonal})^2}$$

$$\text{side} = \sqrt{0.5 \times (1930)^2} = 1365 \text{ mm}$$

As this is less than the available cube height (1435 mm) then this is an acceptable size for the cube. The arrangement of the cube is shown in Figure 4.12.

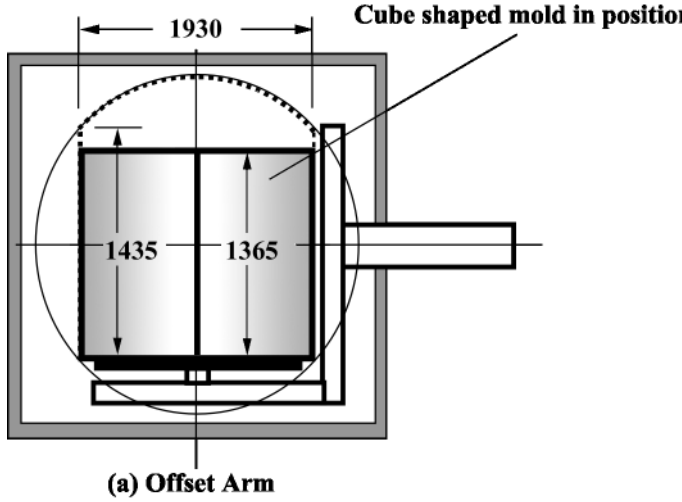


Figure 4.12 Cube mold on offset arm, used with permission of The Queen's University, Belfast

(b) For the straight arm, the largest cube that can be put on the plate will be arranged as shown in Figure 4.13 and the diagonal will be given by

$$\text{diagonal} = \sqrt{2 \times (s)^2}$$

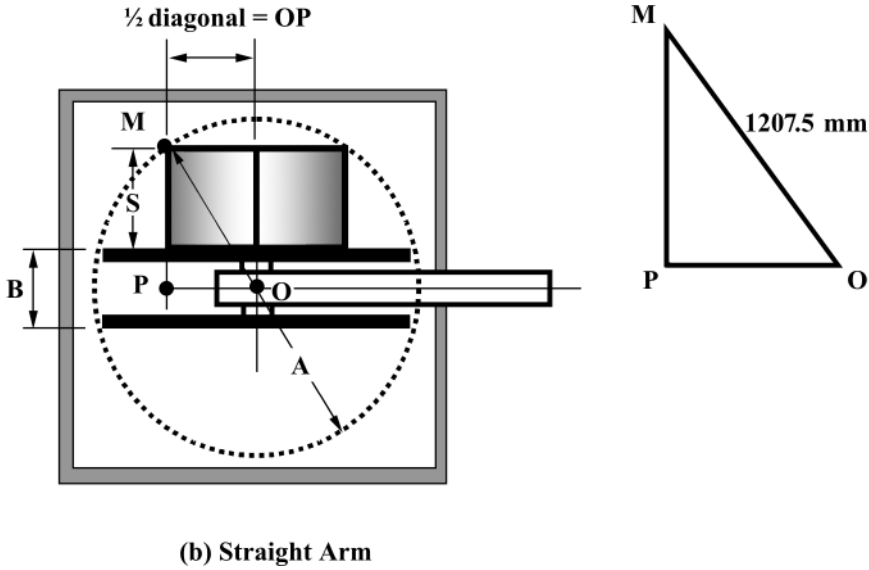
where s is the side of the cube. This will correspond to OP on the triangle OPM, and the height MP is given by

$$MP = s + (B/2)$$

Hence,

$$1207.5^2 = [s + (B/2)]^2 + (0.5\sqrt{2 \times s^2})^2$$

Substituting for B gives the side of the cube, s = 890 mm.



(b) Straight Arm

Figure 4.13 Cube mold swing on straight arm, used with permission of The Queen's University, Belfast

4.2.2 *Mold Speed*

Mold rotation is usually constant throughout the rotational molding process from loading to unloading, and is monitored with tachometers. While the minor (plate/equatorial) and major (arm/polar) rotating speeds are usually programmed by the operator, care must be taken to ensure that the speeds are constant throughout the entire 360° paths followed by the mold. Improperly weight- or counter-balanced mold spiders can cause nonconstant rotation during the rotating cycle. Early machines had a fixed major-to-minor rotation rate ratio of 4:1. Most modern machines have arms that allow independent changes to major and minor rotation rates. This independence increases the versatility in molding odd-shaped parts or complex spider assemblies.

4.2.3 *Speed Ratio*

During rotational molding, the speeds of rotation are slow and the plastic effectively resides in the bottom of the mold. The thickness of the coating of the plastic on the mold wall depends on how regularly each point on the mold surface dips into the powder pool. The speed of rotation and, in a biaxial rotation machine, the ratio of the speeds about the two axes have a major influence on the thickness distribution of the plastic on the mold.

It should be noted that the *actual* speeds of the arm and plate, and their ratio, are most important. As the minor axis drive shaft is often inside the major axis drive shaft, the minor axis speed reading on the molding machine may be higher than the major (arm) speed. The *actual* (relative) speed of the minor axis is lower than the major (arm) speed because it is given by the difference between the machine readings for the minor and major axes. The Speed Ratio (arm/plate) is therefore often defined as

$$\text{Speed Ratio} = \frac{\text{Major Axis (rpm)}}{\text{Minor Axis (rpm)} - \text{Major Axis (rpm)}} \tag{4.1}$$

Thus if the minor axis speed reading on the machine is 15 rpm and the major axis speed is 12 rpm, then the Speed Ratio (arm/plate speeds) is 4:1, which is a common ratio.

Table 4.1 gives typical values of speed ratios (arm/plate) that are recommended for different mold shapes.

Table 4.1 Recommended Speed Ratios for Various Mold Shapes*

Speed Ratio	Shapes
8:1	Oblongs, straight tubes (mounted horizontally)
5:1	Ducts
4:1	Cubes, balls, rectangular boxes, most regular 3-D shapes
2:1	Rings, tires, mannequins, flat shapes
1:2	Parts that show thinning when run at 2:1
1:3	Flat rectangles, suitcase shapes
1:4	Curved ducts, pipe angles, parts that show thinning at 4:1
1:5	Vertically mounted cylinders

* Adapted from recommendations by McNeill Akron Co.

It may be seen from the above that the definition of an appropriate speed

ratio for a particular product is not a precise science. It can depend on factors other than the speed ratio. These include the position of the mold relative to the major and minor axes, and the extent to which the heat source has access to all surfaces of the mold. Modern simulation programs attempt to allow for all these factors and these will be described in more detail in later chapters.

4.3 The Oven

The objective of the first step in rotational molding is to elevate the polymer to temperatures where powder particles stick together, coalesce or sinter, then densify into a monolithic liquid layer adhering to the mold wall. For nearly all commercial processes, room temperature powder is introduced to the hollow metal mold that is also essentially at room temperature. This structure is then immersed in a fluid medium that has a temperature that is sufficiently high to allow the metal mold and powder to increase in temperature to the sinter-densification temperature range.

There are three modes of heat transfer between the cool mold/polymer and the hot medium: conduction, convection, and radiation.

Conduction*:* This mode of heat transfer involves solid-solid contact. It is one way that energy is transmitted from the mold inner surface, through the mold, to the rotating powder, and into the sinter-melt residing on the mold surface. However, it is not a means of heating the mold/powder mass to the molding temperature.

Radiation*:* This is electromagnetic energy interchange between a hot source and a cool sink. There is no physical contact between the source and sink. As a result, surfaces must see each other to achieve radiant energy interchange. Plates and wires are common methods of producing radiant energy. Although radiant energy transmission is the common way of heating plastic sheet in thermoforming, radiation has not been used extensively in rotational molding. The primary reason for this is that the complex shapes of molds and mounting apparatus are not amenable to uniform energy interchange.

Convection*:* This involves fluid-solid contact and it is the common method of heating (and cooling) for rotational molding. Heated fluids can be easily directed over all surfaces of the molds. Some of the fluids used in rotational molding are air, combustion gas products, steam, hot water, oil, and

molten salts. Liquids such as water, oil and molten salts, and steam are usually confined in channels or pipes that are imbedded or fastened against the mold surface. For atmospheric gases such as air, combustion gas products, and occasionally steam, the molds are immersed in the gas flow. The rate of heat addition to the mold/polymer system is defined by the *heat flux, q*:

$$q = h_{\text{convection}}(T_{\text{heating}} - T_{\text{mold}}) \tag{4.2}$$

From this it may be seen that the thermal driving force is the temperature difference between the heating medium and the mold/polymer system. The effectiveness of the thermal driving force is measured by the convection heat transfer coefficient, $h_{\text{convection}}$. Values in British units range from about 1 for stagnant air to 10,000 or higher for condensing steam, as shown in Table 4.2.

Table 4.2 Heat Transfer Coefficients

Fluid	**Convection Heat Transfer Coefficient, $h_{\text{convection}}$**	
	$\times 10^{-3}$ W/cm^2 °C	Btu/ft^2 hr °F
Quiescent air	0.5 – 1	0.8 – 2
Air moved with fans	1 – 3	2 – 5
Air moved with blowers	3 – 10	5 – 20
Direct combustion gas impingement	6 – 10	10 – 20
Air and water mist	30 – 60	50 – 100
Fog	30 – 60	50 – 100
Water spray	30 – 90	50 – 150
Oil in pipes	30 – 180	50 – 300
Water in pipes	60 – 600	100 – 1,000
Steam in pipes, condensing	600 – 3,000	1,000 – 15,000

Note that the energy efficiency increases as the air flow becomes more aggressive. The energy transfer from the convecting fluid to the mold/polymer system is only one of several energy transfer steps in the heating of the polymer to its final molding temperature. The greater the value for the convection heat transfer coefficient becomes, the less important is this aspect of the overall resistance to heat transfer.

Although condensing steam is an extremely efficient heat transfer medium, live steam is usually not used owing to its hazardous nature and its relatively low temperature of 100°C or less. If very accurate temperature

control is required, for example, for thermally sensitive polymers such as PVC or reactive polymers such as nylon, special double-wall molds are used, as described earlier. Hot oil or combustion gases are circulated in the mold cavity. The complexity of the rotating couplings adds to the cost of this option and restricts its use to very specialized applications.

Combustion of natural gas and air mixture yields combustion products having temperatures of 700°C (1292°F) to perhaps 800°C (1472°F). Direct flame impingement can be used if the mold is of thick-walled carbon or high-grade stainless steel and if there is no risk of overheating or thermally degrading the polymer. When aluminum molds are used and/or when the polymer is thermally sensitive for whatever reason, the combustion products are used to heat the air indirectly, which in turn is blown against the mold and framework surfaces. Forced convection or high-velocity circulation and recirculation of oven air provides the most effective mode of air heat transfer. Air velocities over mold surfaces should be at least 1.5 m/s (5 ft/s) in order to obtain adequate heat transfer. Nevertheless, forced air convection heat transfer coefficient values are typically less than those for other modes of convection heat transfer. The traditional heating device is an insulated sheet-metal oven having insulated doors, a gas combustion region, and high-velocity blowers or fans to recirculate the air inside the oven.

4.3.1 *Oven Design*

Electrically generated infrared heat has been used as a primary heating method, but by far the most common method of heating is by means of gas combustion. The key to improved energy efficiency lies in adequate insulation of the oven, optimum burner design, and energy conservation during mold ingress and egress. The following sections consider some aspects of oven design.

Gas Combustion. Two gaseous fuels are commonly used to produce heat in rotational molding ovens — natural gas and propane. The heating values for these are given in Table 4.3. It is estimated that combustion efficiency is about 50%. As an example, for a machine having a 115 inch arm swing, the oven capacity is 4.5 MBtu/hr. The 1995–1996 cost to operate this oven in Northeast Ohio on natural gas was about $22/hr and in upstate New York, about $28/hr.

As mentioned above, the conventional oven for commercial rotational molding machines is a double-walled, heavily insulated sheet-metal box having

a single door for single-carriage shuttle machines or double doors for dual-carriage shuttle and rotary or carousel machines. A slot in one side wall of the oven is needed for the horizontal arm of carousel machines. Traditionally, the door opening method is by pneumatic counterweighted elevator. Swing-open and pleated folding doors are also used. Since room temperature air is mixed with heated oven air whenever the doors are opened for carriage or arm movement, energy efficiency is compromised. Furthermore, since the oven is normally operated under negative pressure to ensure adequate exhaustion of combustion gases and since the oven openings are not sealed, room temperature air is drawn into the oven and further decreases the oven efficiency.

Table 4.3 Characteristics for Combustion Gases in Rotational Molding

Property	Natural Gas	Propane
Approx. weight, lb/ft^3 (Std. conditions)	0.0423	0.1225
Approx. volume, ft^3/lb (Std. conditions)	23.69	8.1
Heating value, Btu/ft^3 @ RT stack	1050	2500
Heating value, Btu/lb @ RT stack	24,000	20,400
Heating value at 400°F flue gas	900	2150
Heating value at 1000°F flue gas	760	1800
Flame temperature, °F, ideal mixture, RT air	3600	3000
Approximate cost, $/lb	—	$0.182*
Approximate cost, $/1000 ft^3	$2.82 (4.15)**	$22.30
Approximate cost, $/MBtu @ RT stack	$2.69 (3.95)	$8.92
Approx. cost @ 50% energy efficiency	$5.38 (7.90)	$17.84

* Northeast Ohio bulk rate, 1996.

** 1995 U.S. national average. Northeast Ohio value in parenthesis. The value range is $1.18 (Alaska) to $5.31 (New York).

As a result, even though the ideal condition is isothermal air temperature, it is seldom achieved in commercial ovens. As noted in the example above, energy efficiency is estimated to be 50%, and could be substantially less than this.[8] Note that in the equation given above, if the heating temperature is lowered, the amount of energy transferred to the mold assembly is reduced.

Newer oven designs incorporate adjustable baffles, and dead zones in three-dimensional corners have been eliminated in order to improve air circulation around the rotating mold assembly. Older oven designs recirculate oven air past a plenum that separates the burner combustion gases from the oven air. The combustion gases are then vented. Recently, high-intensity, high-

efficiency burners have been developed that incorporate recirculating oven air. Primary energy conversion efficiency has been dramatically improved. Furthermore, high-intensity fans having several inches of water column pressure capability, allow 20–30 air changes in the oven per minute. Higher air velocities across the mold surface result in a high heat transfer coefficient, and improved mold heating rate.

4.3.2 *Heat Transfer in Oven*

Although a detailed and precise analysis of heat transfer in a rotational molding oven is complex due to the transient nature of the effects, it is possible to quantify some aspects of the system using relatively simple procedures.

The steady heat transfer rate, Q, through a material is given by

$$Q = UA\Delta T \tag{4.3}$$

where ΔT is the temperature difference between the faces of the material, A is the area exposed to the heat transfer, and U is the thermal transmittance coefficient.

An alternative and very convenient way to express this equation is in terms of a thermal resistance, R, where

$$R = \frac{1}{UA} \tag{4.4}$$

For the three modes of heat transfer referred to above, the thermal resistance is expressed as:

Conduction: The thermal resistance for conduction is given by

$$R_d = \frac{d}{KA} \tag{4.5}$$

where d is the thickness of the material and K is the thermal conductivity of the material.

Convection: The thermal resistance for convection is given by

$$R_v = \frac{1}{hA} \tag{4.6}$$

where h is the heat transfer coefficient. As described earlier, its value depends on the conditions at the surface layer between the solid and the fluid. It is influenced by the surface geometry, the nature of the fluid motion, and a variety of other thermodynamic parameters.

Radiation: The thermal resistance for radiation is given by

$$R_R = \frac{1}{h_r A} \tag{4.7}$$

where

h_r is an effective radiation heat transfer coefficient which is given by

$$h_r = \frac{1}{\varepsilon \sigma A T^3} \tag{4.8}$$

where ε is emissivity
σ is Stefan Boltzmann constant
A is area, and
T is temperature

Using the above thermal resistance terms it is possible to analyze the heat transfer rate through quite complex systems. Consider a typical situation where two solid materials *a* and *b* are in contact with each other and with fluids at different temperatures as shown in Figure 4.14.

The heat transfer rate through this system can be expressed in a variety of ways based on the thermal resistances shown as equivalent electrical resistances in Figure 4.14. Firstly, the heat transfer rate can be related to the overall temperature difference ($T_1 - T_5$).

$$Q = \frac{T_1 - T_5}{R_h + R_a + R_b + R_c} \tag{4.9}$$

$$Q = \frac{T_1 - T_5}{(1/h_h A) + (d_a/K_a A) + (d_b/K_b A) + (1/h_c A)} \tag{4.10}$$

Alternatively, the heat transfer rate can be related to the temperature difference across each element, as shown below.

$$Q = \frac{T_1 - T_2}{(1/h_h A)} = \frac{T_2 - T_3}{(d_a/K_a A)} = \frac{T_3 - T_4}{(d_b/K_b A)} = \frac{T_4 - T_5}{(1/h_c A)} \tag{4.11}$$

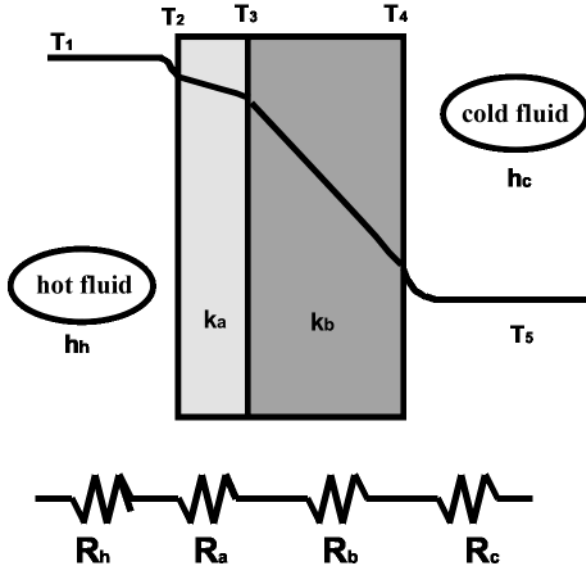


Figure 4.14 Heat transfer through two solid materials *a* and *b*, used with permission of The Queen's University, Belfast

It should be noted that on some occasions the thermal resistances can be in parallel instead of in series, as in the above case. If the resistances are in parallel then they must be added like parallel electrical resistors. This is illustrated in the following numerical example.

Example 4.2

The oven in a rotational molding machine is in the shape of a cube as shown in Figure 4.15. If the walls consist of 10 mm thick metal with a thermal conductivity of 50 W/m K and insulation with a thermal conductivity of 0.15 W/m K, calculate the thickness of the insulation material if the temperature of the outside surface of the oven is not to exceed 45°C when the oven temperature is 350°C and the outside air temperature is 25°C. The inside and outside heat transfer coefficients are 35 W/m^2 K and 25 W/m^2 K, respectively. The effective radiation heat transfer coefficient for the inside walls of the oven is 30 W/m^2 K.

Solution

Referring to the thermal (or equivalent electrical) circuit in Figure 4.15, we can apply an energy balance at any surface or node. For example, at the

outer surface of the oven the heat transfer rate into this node must equal the heat transfer rate out of this node. Before expressing this as an equation, it is worth noting that the radiation heat input from the mold and the convection heat input to the inside surface of the oven are in parallel and so must be added like parallel electrical resistors, that is

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_r} + \frac{1}{R_v} = \frac{1}{(1/h_r A)} + \frac{1}{(1/h_h A)} \tag{4.12}$$

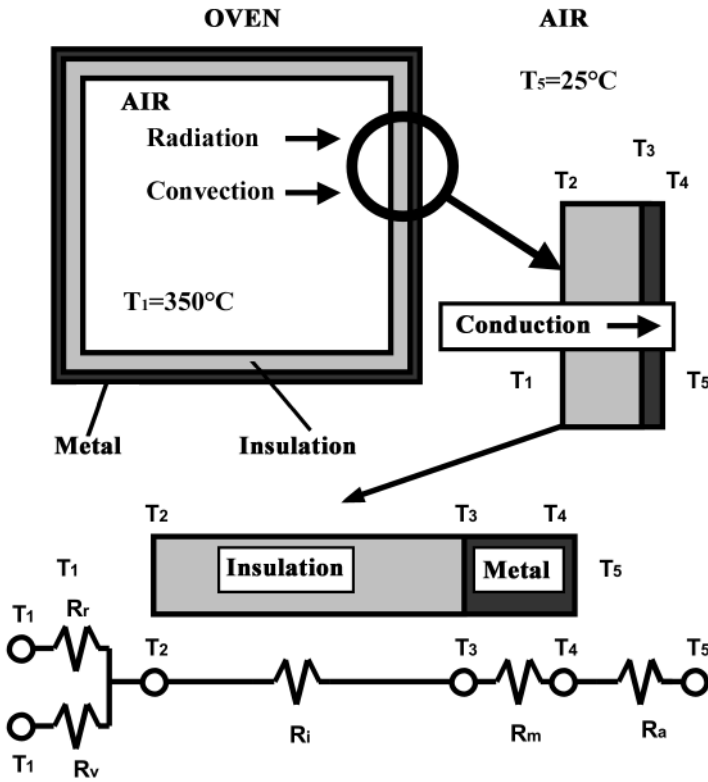


Figure 4.15 Thermal resistance diagram for rotational molding oven, used with permission of The Queen's University, Belfast

The energy balance at the outer surface of the metal gives

$$\text{Energy}_{\text{in}} = \frac{T_1 - T_4}{\sum R_t} \tag{4.13}$$

where

$$\sum R_t = \left(\frac{1}{1/h_r A} + \frac{1}{1/h_h A} \right)^{-1} + \frac{d_a}{K_a A} + \frac{d_b}{K_b A} \tag{4.14}$$

And the energy out is given by

$$\text{Energy}_{\text{out}} = \frac{T_4 - T_5}{(1/h_c A)} \tag{4.15}$$

Equating the *Energy In* to the *Energy Out* and rearranging to get the thickness of the insulation yields:

$$d_a = \left(\frac{K_a}{h_c} \right) \left[\frac{(T_1 - T_4)}{(T_4 - T_5)} \right] - \left[\frac{K_a}{(h_r + h_h)} \right] - K_a \frac{d_b}{K_b} \tag{4.16}$$

Using the data given in the question

$T_{\text{air}} = 25$ $T_a = 350$ $h_c = 25$ $h_h = 35$ $h_r = 30$

$d_b = 0.01$ $T_0 = 45$ $K_a = 0.15$ $K_b = 50$

the required thickness of the insulation is 89 mm. It should be noted that due to the high thermal conductivity of the metal and its relative thinness, it offers very little resistance to heat transfer by conduction. The thickness of the insulation required is directly proportional to its thermal conductivity. Also, in this calculation any radiated heat from the wall being analyzed has been ignored.

4.3.3 *Oven Air Flow Amplification*

It was noted in the oven design section that heating efficiency depends on effective air flow around the mold surface. There are two practical issues that have an adverse influence on effective and uniform air flow across the entire mold assembly. Rotational molding has traditionally long cycle times. As a result, molders frequently tier mold assemblies in order to make more efficient use of the swept volume of the arm. Air circulation to the inner surfaces of these tiered assemblies is often impeded by outside molds and the architecture of the spider supports, and nonuniform heating and cooling results. Efficient energy transfer can be impeded even when single molds or single-tiered spiders are used. Consider a part with

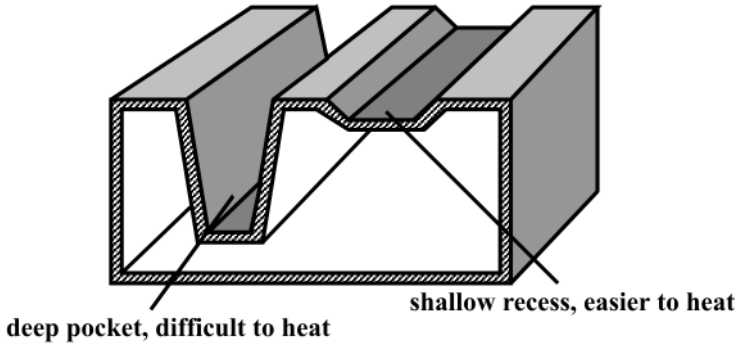


Figure 4.16 Mold showing deep pocket that is difficult to heat, used with permission of The Queen's University, Belfast

a pocket or recess as shown in Figure 4.16. In some cases, vanes or baffles are welded to the mold surface or to the spider to help deflect air flow (Figure 4.17). For deeper recesses, it is very difficult, if not impossible, to get high-velocity air to the bottom of the inner mold surfaces simply by baffling. Currently, a limited flow of high-velocity air, supplied through a hollow element in the arm, is fed to a venturi or air amplification device or air mover. As the high-velocity air flows into the throat of the venturi, it draws heated oven air into the inlet, and propels it against the mold surface, sometimes in a swirling motion to improve heat transfer as illustrated in Figure 4.18.

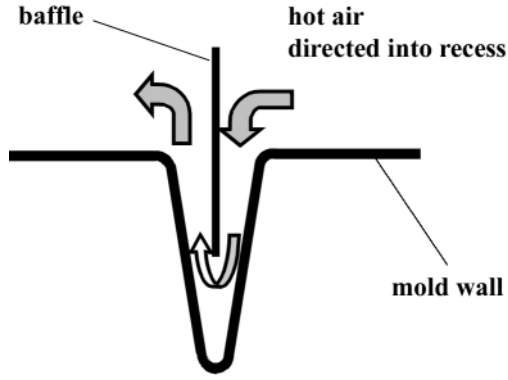


Figure 4.17 Mold showing baffle at deep pocket, used with permission of The Queen's University, Belfast

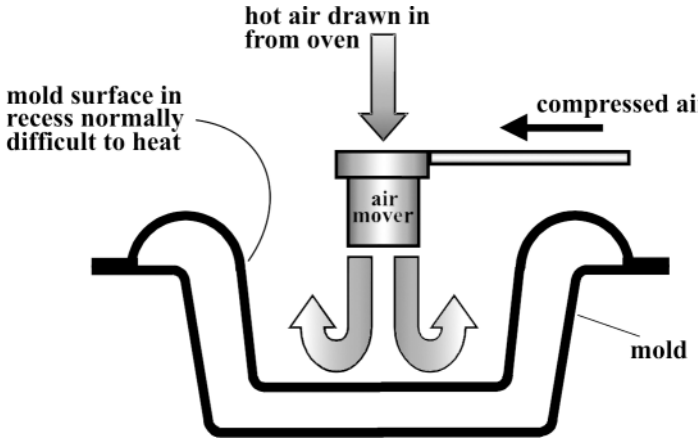


Figure 4.18 Use of air mover to heat deep pocket in mold, used with permission of The Queen's University, Belfast

4.4 Cooling

Once the plastic has melted into a monolithic structure against the mold inner surface, the plastic, the mold, and the ancillary supporting structure must be cooled. If a liquid is used to heat the mold, a valve system on the liquid flow lines is used to switch to cooling liquid. More complex systems, such as parallel heating and cooling flow paths through the mold, could be used but are usually reserved for nonrotating molds such as injection molds.

The most popular cooling media are water and air, into which the mold assembly is immersed. Most commercial rotational molding machines are equipped with both and many have options such as water spray, water mist/fog, etc. As discussed elsewhere, sprayed water is an extremely effective way of reducing mold assembly temperature, but quenching may not always be the coolant of choice. As cooling normally occurs from the outside only, fast cooling results in unsymmetrical crystallite structure formation across the part wall, which leads to warpage. Typically, sequential applications of still air, forced air, water mist, or fog are used to alleviate warpage problems. On a carousel machine, if cooling does not control the rotational molding cycle, cooling may be done gently using only convected room temperature air.

Commercial machines have at least one cooling station and at least one method of cooling. Controlled shrinkage and minimum warpage are the keys to successful cooling. While there are certain thermal guidelines to successful

cooling, such as polymer temperature profile inversion, discussed elsewhere, fine-tuning of the cooling cycle is usually by trial-and-error. The typical water cooling station is a galvanized or stainless steel sheet-metal box, with a corrosion-resistant floor having adequate drain holes. There are many types of water jetting or spraying nozzles. If drenching is needed, high volume flow "shower heads" are mounted above the mold assembly. Fog or fine mist nozzles are usually mounted at the corners of the cooling chamber, to provide a suspended "cloud" of moisture droplets with low settling velocity. This allows the mold assembly to pass through the cloud and leads to more uniform cooling. Fog and mist nozzles are recommended when the mold is relatively thin or when the polymer cannot be thermally shocked by flooding or drenching. Chemically treated and conditioned water is always recommended, to minimize scale build-up and rusting of steel parts on the mold assembly. Nearly all commercial operations using water recycle the water for economic reasons.

Air-moving fans are selected for high-velocity, high-volume flow. Blowers are sometimes used, but compressor-blowers are usually not used. Positive ventilation is needed in the cooling station if the polymer outgases noxious fumes such as HCl from PVC. From a mechanical viewpoint, there is little point to rotating the mold when the polymer is below the melting temperature or glass transition temperature. With crosslinked materials the rotations could stop as soon as the mold leaves the oven. However, to provide uniform cooling, the mold assembly is usually rotated in the cooling environment throughout the cooling cycle.

4.5 Process Monitors

Although oven temperature is considered to be constant throughout the heating process, this is not the case. Oven air temperature drops when the oven doors are opened at the beginning and end of the heating cycle. The oven temperature can overshoot the target value by 30°C (50°F) or so before settling onto the set-point temperature. Also, it has been shown repeatedly[8, 9] that on the vast majority of machines, the oven temperatures are not uniform throughout the oven, even at the end of the heating cycle. And most certainly, the mold temperature never reaches the set temperature of the oven. The mold temperature is changing throughout its time in the oven, and since this is what influences the plastic temperature, it is apparent that complex transient heat transfer phenomena are taking place throughout the cycle. Some of the mold temperature changes are

attributable to oven design and some to the inherent obstruction in air flow due to mold/spider structure on the arm itself. All of this calls into question the control strategy for rotational molding machines, which is normally based on the temperature of a thermocouple located in a remote corner of the oven.

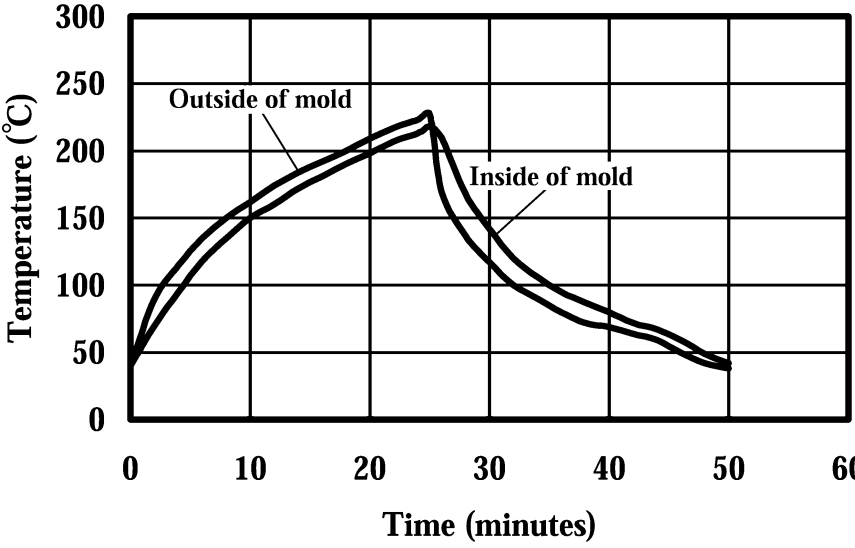


Figure 4.19 Variation of mold temperature for oven set temperature of 300°C, used with permission of The Queen's University, Belfast. Mold wall thickness = 5.5 mm, part wall thickness = 6 mm

As noted elsewhere, the mold/polymer/spider heating rate is essentially a first-order response to a step change in environmental temperature:

$$\frac{T_a - T}{T_a - T_0} = e^{-\frac{h\alpha t}{Kd}} \tag{4.17}$$

where T_a is the heated air temperature, T_0 is the initial mold assembly temperature, T is the instant mold assembly temperature, h is the convection heat transfer coefficient, α is the thermal diffusivity of the mold assembly, K is its thermal conductivity, d is the effective thickness of the mold assembly, and t is the time since insertion into the heated air. The importance of this equation is discussed in Chapter 6. The exponential rise in mold temperature predicted by this equation has been confirmed by experimental measurements as shown in Figure 4.19. These results were

obtained by attaching thermocouples to the mold, on its surface, and through the mold thickness, and transmitting the data to a computer as the mold rotates. Infrared detectors have been used to measure mold surface temperatures[10–12] and have shown similar temperature profiles.

Extensive trials have shown that the most reliable means to control the process is based on the temperature of the air inside the mold.[13] A variety of commercial systems are available to do this, but at this stage, none have been used to directly control the rotational molding cycle. This is likely to happen in the near future as cycle times are reduced and more robust insulation becomes available to protect the sensitive electronics when the equipment is used on hot air machines. The development of high temperature slip rings to take electrical signals from the mold and the use of ovenless machines also make this type of process control relatively straightforward. The basis of this type of process control is discussed next.

4.5.1 *Internal Air Temperature Measurement in Rotational Molding*

In the vast majority of cases, the rotational molding process involves heating a powdered plastic in a rotating metal mold. Normally the heating is done in an oven and this is the situation that will be considered now. With proper measuring equipment, time-dependent oven temperature, mold temperature, and the temperature of the air inside the mold can be obtained, as shown in Figure 4.20. These data have characteristic shapes that are unique to rotational molding, particularly the internal air temperature trace.[13]

Consider the temperature traces in Figure 4.20 in detail.[14] The set temperature for the oven is 330°C (626°F). When the cycle starts, oven environmental air temperature immediately starts to increase toward a predetermined set temperature. However, it is several minutes before the temperatures of the mold, the plastic, and the air inside the mold begin to increase. The lower line in Figure 4.20 is the temperature of the air inside the mold. The two lines above it are the temperatures of the outside surface and inside surface of the mold. In the oven the outer surface has the higher temperature and in the cooling chamber the outer surface is the cooler of the two.

The temperature trace for the air inside the mold provides the most interesting information. Once the internal air temperature begins to increase, it increases steadily. Up to Point A there is no powder sticking to the mold because the plastic has not reached its “tacky” temperature. The rotational

speeds of the mold about the two perpendicular axes are not critical during this period as the powder is simply tumbling about in the mold. If a graphic has been placed in the mold it is generally recommended to use slower speeds during this initial period to avoid scuffing the graphic off the mold wall.

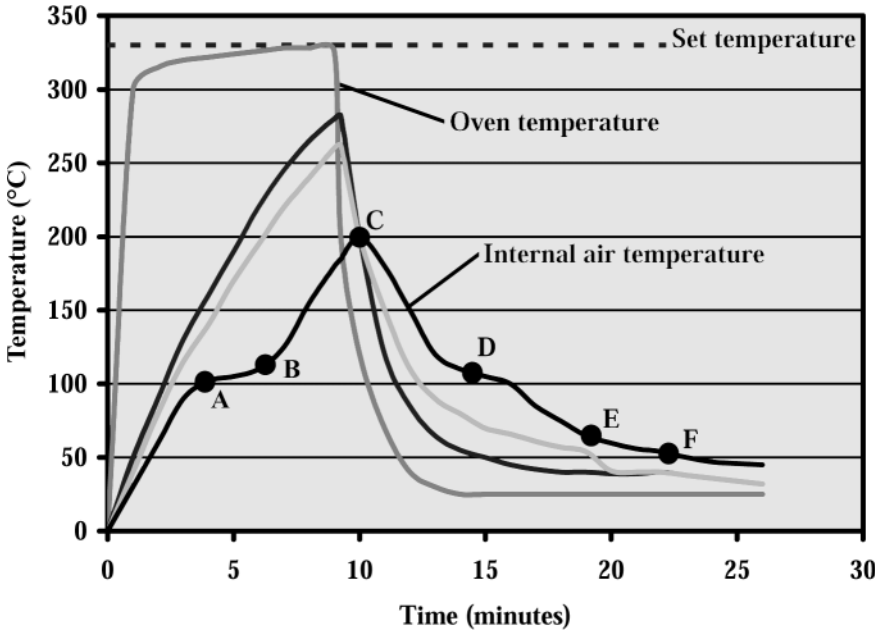


Figure 4.20 Typical temperature traces for a rotational molding cycle, used with permission of The Queen's University, Belfast

At Point A the plastic powder is sufficiently hot to start sticking to the mold. With polyethylene this stage is usually reached when the inner air temperature reaches a value of about 100°C (212°F). The rate of increase of the internal air temperature now slows because the melting of the plastic absorbs the thermal energy being put into the system. This continues for several minutes, until at Point B all the plastic has adhered to the mold wall and there is no longer loose powder tumbling about in the mold. The internal air temperature then starts to increase at approximately the same rate as in region OA. The plastic is now stuck to the wall of the mold as a loose powdery mass, some of which will have already started to sinter and densify. During the region BC, the sintering process is completed as the powder particles coalesce to form a uniform melt.

When the powder particles are laying against the mold wall, they trap

irregular pockets of gas as illustrated at stage 1 in Figure 4.21. These pockets gradually transform into spheres (stage 2) and over a period of time they diffuse out of or dissolve into the plastic. It should be noted that the pockets of gas ("bubbles") do not push their way through the melt because the molten plastic is too viscous to allow this to happen.[15–24] This process of removal of the bubbles from the melt is extremely important in rotational molding and will be discussed in detail in Chapter 6.

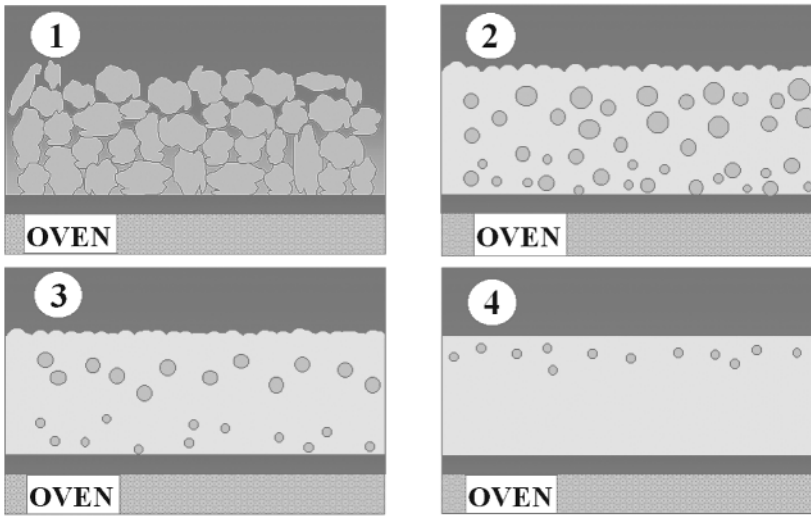


Figure 4.21 Bubble formation and removal in rotational molding, used with permission of The Queen's University, Belfast

For practical reasons molders usually seek stage 4 in Figure 4.21. That is, they take a slice through the thickness of a molded part and check that there are still some bubbles left at the inner free surface. This is regarded as the correct level of "cooking" for the plastic. An even better molding is obtained when the bubbles just disappear totally, but of course if the molder looks at a section that has no bubbles, there is no way of knowing if the bubbles have just disappeared or perhaps had disappeared many minutes previously. Once the bubbles disappear, degradation processes start to have an effect very rapidly. So it is better to be "under-cooked" rather than "over-cooked."

This is where the internal air temperature trace is very useful because extensive trials have shown that independent of any other machine variable, the bubbles will have just disappeared when the internal air temperature reaches a critical value. Typically, for rotational molding grades of polyethylene this is

about 200°C (392°F). Thus, by ensuring that this value of internal air temperature is always reached, the molder is able to produce a good molding every time. At this point the mold can be taken out of the oven and the cooling stage begins. It should be noted in Figure 4.20 that it is not uncommon for the temperature of the internal air to continue rising after the mold comes out of the oven. This is particularly the case if the wall of the plastic part is quite thick. Therefore it is necessary to allow for this overshoot when determining the optimum time in the oven.

Once cooling begins, the internal air temperature starts to decrease. The rate of decrease will depend on the type of cooling, in addition to part wall thickness and mold thickness. Water cooling causes a rapid drop in temperature whereas air cooling is gentler. During the initial period of cooling, the plastic adhered to the mold wall is still molten. Its crystalline structure or morphological characteristics are being formed and the rate of cooling will have a major effect on the morphology of the end product. Properties such as impact strength and physical characteristics such as shrinkage and warpage are affected dramatically by the cooling rate.

At a certain point the slope of the internal air temperature trace changes markedly (Point D). This is associated with the solidification of the plastic. As it solidifies and crystallizes, the plastic gives off heat which means that the internal air is not able to decrease in temperature as quickly as before. Once the plastic has become solid across the wall section, the internal air temperature starts to decrease again at a rate similar, but usually slower, than the rate occurring before solidification began. As the plastic is now solid, the rate of cooling has less effect on the morphology of the plastic. Therefore fast cooling, using water, is permissible. The only thing that one has to be careful about is the unsymmetrical cooling across the wall thickness, if the mold is cooled from the outside only. This will tend to cause warpage. This phenomenon will be discussed in detail later.

The final important stage in the cycle is Point E. It may be seen in Figure 4.20 that this is characterized by a slight change in slope of the internal air temperature trace. This indicates that the plastic is separating from the mold wall and an insulation layer of air is forming between the plastic and the mold. This means that the external cooling becomes less efficient and so the internal air temperature cannot decrease as quickly as before. It may be seen in Figure 4.20 that the temperatures of the inner and outer surfaces of the mold become equal after this point. Eventually Point F, the demolding temperature, is reached.

4.5.2 *Infrared Temperature Sensors*

Infrared sensors provide a convenient means of remote measurement of temperature. In the context of rotational molding, where the motion of the mold makes hard wire measurements difficult, infrared technology has the potential to be very useful. However, the rotating molds and associated framework add complexity to the interpretation of the data received from the infrared sensor. The detector/camera is permanently mounted on the wall of the oven. Since the molds rotate through the infrared field, a video camera is necessary in order to ensure that the temperature being measured is that of the mold, rather than that of the nonmold hardware, oven walls, or the supporting arm. Although reflection from the mold surface can mislead the infrared detector, the effect is usually quite transient. The approach taken has been to treat the data collected as a map of the surface of the mold, and by sampling data at high rates, smoothing techniques can be used to get an average temperature profile for the mold.[10] This can then be used to activate key steps in the machine cycle, such as moving from the heating stage to the cooling stage. It is important to note that infrared systems need regular calibration using some other temperature measuring system.

4.6 Servicing

There needs to be a physical location in the rotational molding environment where the empty molds are inspected, cleaned, dried if necessary, charged with powder, where inserts and vent tubes are installed, and where the molds are closed and sealed. There also needs to be a physical location where the molds are unsealed and opened and where the parts are removed. Usually these servicing steps, usually called load/unload stations, are at the same physical location. Manpower requirement is high at this location, since many events are happening during loading and unloading. For many home-built machines, molds are opened and closed manually, parts are removed manually, and molds are inspected and charged manually. Parts need to be physically removed from this station and powder and inserts need to be physically delivered to this station. A growing trend in commercial machines is to have automation in the service areas, particularly in regard to dispensing material into the mold. In some cases there may also be automated mold opening, although there are few instances of robots being used in this industry.

4.7 Advanced Machine Design

For decades, rotational molding has been viewed by the plastics industry as a relatively simple mechanical process involving heating the mold/polymer system while rotating the assembly about the two perpendicular axes. The major limitation to this powder-based process has always been the long cycle time at an elevated temperature. While in theory most thermoplastics and thermosets should lend themselves to rotational molding, many polymers are simply too thermally sensitive for the current processing conditions. And many resin suppliers, not viewing rotational molding as an economically important process, have chosen not to alter their polymers to meet the unique demands of rotational molding. As a result, polyethylene, in all its variations and through its normally thermally stable nature, has become the polymer of choice. As one considers ways to improve machine design and, in particular, to reduce manufacturing costs, it is important to realize that materials, molds, and molding machinery all have a part to play in such developments. Although the heat transfer processes are inherently slow in hot air oven machines, as discussed above, a major contributory factor to long cycle times is the thickness of the molded part and the fact that it is heated/cooled from one side only.

The fact that most rotationally molded parts are made from polyethylene means that shape must be used very effectively to compensate for the low elastic modulus of this plastic. As will be discussed later, where possible, corrugated sections, kiss-off points, and other geometrical features are used to impart stiffness to the end product. And of course thickness of the part is a major factor in this. The transverse or flexural stiffness of a material is proportional to the cube of the thickness. Doubling the thickness gives a factor of 8 improvement in stiffness. Not surprisingly therefore, most rotationally molded parts are very much thicker than equivalent injection molded products.

There is a vicious circle therefore in that the molder uses polyethylene and so the wall thicknesses must be large to achieve any reasonable properties in the molding. This results in long cycle times and this in turn means that the process is restricted to polyethylene. If the rotational molding process had access to higher modulus materials, the walls could be thinner, which means that the cycle times could be shorter and so thermal sensitivity would become less of an issue. Of course in addition to access to higher modulus materials, there must be more efficient heating and cooling to minimize the exposure of the plastic to the elevated temperatures.

It is well known that thermally sensitive polymers, such as cellulosics, acrylics, and even styrenics, have been rotationally molded, primarily by altering the atmosphere inside the mold. One well-practiced method is the introduction of dry ice pellets along with the powder charge to the mold cavity. In the past, only a few commercial machines had hollow arms that allowed inert gases such as carbon dioxide and/or nitrogen to be introduced directly into the mold through the vent hole system. This hollow-arm concept has been developed further in recent years. Now, most commercial machines have multiple flow channels through the arms.[25] This allows for flow of inert gas to the mold assembly, as well as flow of pressurized air for such activities as air flow amplification and drop box activation, as discussed later. The ability to draw a vacuum or negative pressure and to provide positive pressure has become increasingly important as more is understood about the sinter-densification and cooling characteristics of rotationally molded polymers. The importance of this is discussed elsewhere.

Over the past decade a lot of technical information has been accumulated on the rotational molding process. Over the next decade it will be essential that the industry applies this knowledge to make major improvements to the performance of the molding equipment. Cycle times must be reduced to a fraction of what they are today so that rotational molding can remain competitive against industrial blow molding and emerging technologies such as twin sheet thermoforming and gas assisted injection molding. The use of direct mold heating/cooling needs to be perfected, the use of internal heating and cooling must be incorporated into commercial machines and the benefits of mold pressurization need to be realized.[18, 19, 21, 26–28] This will require a concerted effort from material suppliers, mold manufacturers, and machinery builders to combine the best practice from each sector and advance the industry for everyone.

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5 MOLD DESIGN

5.0 Introduction

In the rotational molding industry, the vast majority of molds are made from metal. Molds made from fiberglass or other types of composite are used for some specialist applications, but most commercial molds are made from sheet steel, nickel, or cast aluminum. The molds are relatively thin shell-like structures because, unlike injection or blow molding, the forces on the mold are small and heat must be transferred quickly to and from the mold. In most cases, the complexity and size of the part dictates the type of metal and method of manufacture used for the mold. For large parts with simple shapes, such as tanks, molds are best fabricated from rolled sheet-metal, either carbon steel or stainless steel. For highly detailed parts, such as doll heads, and where liquid vinyl is used to produce the part, electroformed nickel is recommended.

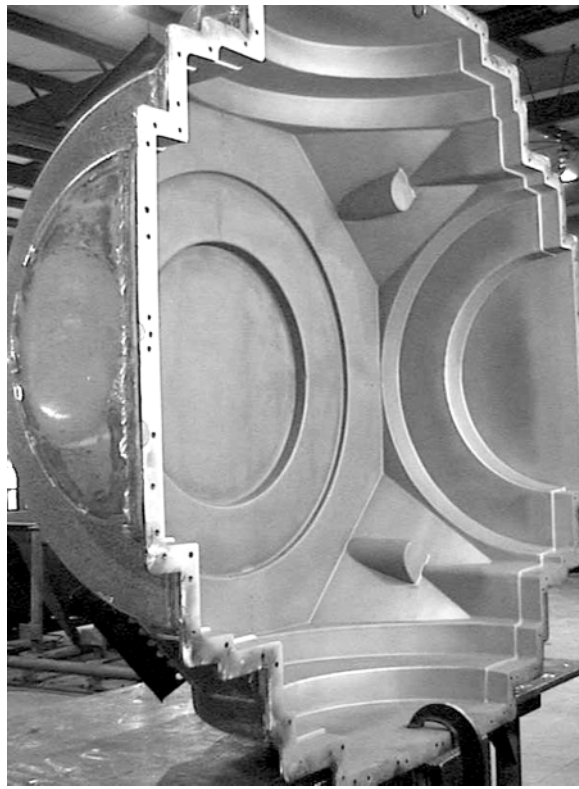


Figure 5.1 Sheet-metal mold, courtesy of Riversmetals, USA

Cast aluminum is used for products that are small to medium in size and have some degree of complexity. Examples include transportation ducting, gasoline tanks, and outdoor toys. Certain areas of the world also tend to favor particular mold materials — for example, aluminum molds are preferred in North America whereas sheet steel molds are more common in Europe and Australasia. Examples of sheet-metal and cast aluminum molds are shown in Figures 5.1 and 5.2.

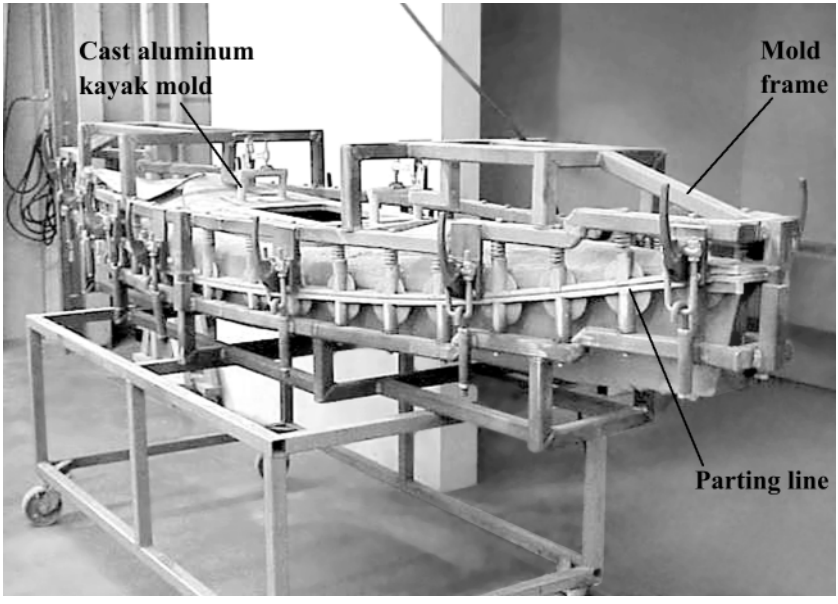


Figure 5.2 Cast aluminum mold, courtesy of Lakeland Molds, USA

Table 5.1 Properties of Mold Materials

Material	Density, ρ kg/m^3 (lb/ft^3)	Thermal Conductivity, K, W/m K (Btu/ft h F)	Specific Heat Capacity, C_p J/kg K (Btu/lb F)	Elastic Modulus, E GN/m^2 (Mlb/in^2)	Coefficient of Linear Thermal Expansion, α_T 10^{-6} K^{-1}
Aluminum (Duralumin)	2800 (175)	147 (153)	917* (0.4)	70 (10.2)	22.5
Nickel (Monel 400)	8830 (551)	21.7 (22.6)	419 (0.18)	179 (26)	14.1
Carbon steel (medium C)	7860 (491)	51.9 (54)	486 (0.21)	206 (29.8)	12.2
Stainless steel (304)	7910 (494)	14.5 (15.1)	490 (0.21)	201 (29.2)	16.3

* Value for pure aluminum

5.1 Mold Materials

Many metals and many grades of metals are used in rotational molding. Typical characteristics of mold materials are given in Table 5.1.

5.1.1 *Sheet Steel*

Standard sheet-metal gages are given in Table 5.2. Even though rotational molding is considered to be a zero pressure process, thin sheet-metal molds may collapse during cooling if the vent hole becomes blocked. Under these conditions, sufficient air cannot re-enter the mold during the cooling phase and a partial vacuum occurs inside the mold. In addition, for very large molds, excessive sagging of the mold wall may occur under the unsupported weight of the mold wall. Making the mold wall thicker is not an attractive solution because, for example, stainless steel has a thermal conductivity of about one-tenth that of aluminum. As a result, thick steel molds heat much more slowly than aluminum molds.

Table 5.2 Data for Sheet-Metal Gage

Gage	Thickness mm (inch)	Weight kg/m^2 (lb/ft^2)
10	3.57 (0.1406)	27.46 (5.625)
12	2.78 (0.1094)	21.36 (4.375)
14	1.98 (0.0781)	15.26 (3.125)
16	1.588 (0.0625)	12.21 (2.5)
18	1.27 (0.0500)	9.765 (2.0)
20	0.952 (0.0375)	7.324 (1.5)
22	0.794 (0.0312)	6.1 (1.25)

Sheet steel molds are fabricated using conventional metal forming methods and welding. While conventional arc welding is usually satisfactory for most low-volume applications, MIG or inert gas welding is recommended where porosity and blowholes might be problems. Although most sheet-metal mold shapes are simple, such as tanks or piping junctions and joints, more complex shapes are manufactured using more advanced metal forming techniques such as pressure rolling and hydroforming.

Low carbon steel is usually considered satisfactory for most low-volume applications, although galvanized steel is used in certain instances where rust-

ing may be a problem. Stainless steel, particularly the 300 series of weldable stainless steels, is used when chemical attack from polymer decomposition or off-gassing is anticipated, or when corrosion of the mold is a problem due to the type of cooling used, or because the molds need to be stored outdoors. It should be remembered that stainless steel is much softer than carbon steel and has a much lower thermal conductivity than carbon steel. Usually, steel molds have no texture or are coarse grit-blasted to a matte finish.

5.1.2 *Aluminum*

Aluminum sheet can be formed and welded into simple shapes using technology similar to that for steel sheet-metal. Aluminum has excellent thermal conductivity but is much softer and less stiff than stainless steel. As a result, aluminum molds tend to have thicker walls than carbon or stainless steel molds. Aluminum is easily machined and can be relatively easily textured with grit blasting and chemical etching. Computer numerically controlled (CNC) lathes are cost-effective ways of machining aluminum when many small molds are required. Figure 5.3 shows an example of an aluminum mold made by CNC machining.

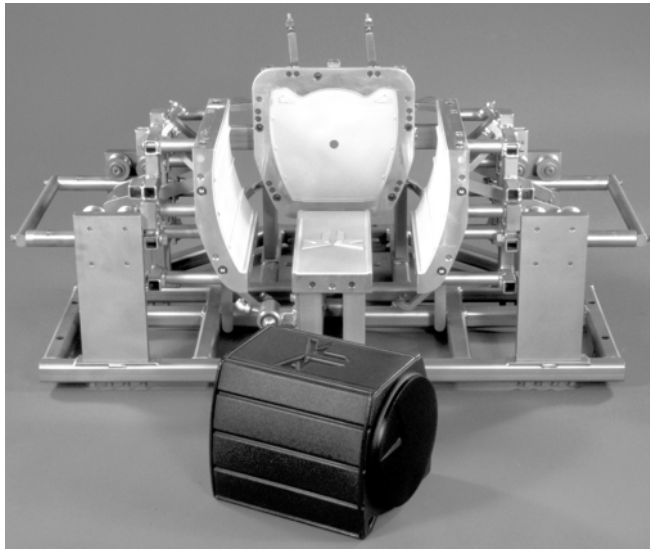


Figure 5.3 Rotational mold made by CNC machining, courtesy of Spin Cast, USA

By far the most common way of producing aluminum molds is by casting. There are three general casting approaches. Atmospheric casting relies

on open ladling or pouring of molten aluminum into a foundry casting. Pressure casting places the foundry casting in a sturdy support frame, and the ladled molten aluminum is forced into the casting under pressure of 350 kN/m^2 (50 lb_f/in^2) or more. Pressure casting costs more than atmospheric casting but the casting has substantially fewer defects such as grain, granularity, "dry sockets," and vacuum pinholes. Vacuum casting is similar to atmospheric casting, but a partial vacuum is applied to the risers during ladling, allowing the air to be drawn from the casting ahead of the molten flow.

Aluminum casting begins with a pattern of the part desired. This pattern is manufactured of wood, plaster, or other prototype substance. The mold pattern is fashioned over the part pattern using plaster, air-hardening clay, or other relatively stiff substance. For part patterns having undercuts, a curable latex or silicone rubber is used. Mold pattern dimensions must be 3.5 to 4% greater than those of the part pattern to account for shrinkage of the polyethylene polymer as it cools. At this time, vent locations, parting line designs, and draft angles must be incorporated, as described later. Sand casting and plaster casting are two common ways of producing the required geometry. Petrobond, sodium silicate or water glass, and Airset are common special sands used in sand casting. The sand casting is made in two pieces with a planar face or parting surface between. The bottom of the mold or "flask" is called the "drag." The top of the flask is called the "cope." The mold pattern defines several aspects of the sand casting. For example, it establishes the mold cavity. If the pattern is flat, the mold cavity is placed in the drag. If it is three-dimensional, care must be taken to place the largest portion in the drag. If it is concave, the pattern is placed in the cope. Furthermore, the pattern establishes points for subsequent drilling and tapping and for alignment with the other portions of the mold cavity. And the pattern establishes the flow system for the molten aluminum, including the pour cup, sprue, runners, gates, and risers. Nearly all molds are poured at a single pouring. The clay graphite crucible can be simple, allowing for skimming and degassing, or can be self-skimming or bottom pouring. The last two are more expensive crucibles and are less easy to maintain, but clean, unoxidized molten aluminum is introduced to the mold. In many cases, nonplanar parting lines are required in the cast aluminum mold. The skill of the casting house is best assessed when freshly cast mold sections are mated for the first time. A rough casting of an aluminum mold is illustrated in Figure 5.4.

If the mold is to be used without additional finishing or if a very high finish is required, casting plaster is used instead of sand. Typical casting plas-

Figure 5.4 Rough cast aluminum mold, courtesy of Norstar, USA

ters are indicated in Table 5.3. The key to quality plaster casts is thorough and extensive oven drying of the plaster after fabrication. Moisture in the plaster is converted to steam when the plaster is contacted by molten aluminum, and cracking or even an explosion can result. All casting molds, whether sand or plaster, are destroyed when the casting is removed.

Table 5.3 Molding Plasters

Commercial Name	Source	Water Ratio (pph)	Setting Time (mins)	Dry Compressive Strength MN/m^2 (lb_f/in^2)
Pattern shop Hydrocal A-11	U.S. Gypsum	54–56	20–25	22.1 (3,200)
Industrial White Hydrocal	U.S. Gypsum	40–43	20–30	38 (5,500)
Ultracal 30	U.S. Gypsum	35–38	25–35	50.3 (7,300)
Densite K5	Georgia Pacific	27–34	15–20	65.5 (9,500)
Super X Hydro–Stone	U.S. Gypsum	21–23	17–20	96.5 (14,000)

5.1.3 *Electroformed Nickel*

The nickel plating process has been modified to produce molds for the blow molding, thermoforming, and rotational molding industries.[1] The

process begins with the part pattern, as described above. The parting line is defined and half the pattern, along with additional pattern construction of the parting line geometry, is carefully isolated from the other half. This portion is then coated with an electrically conducting grease or polyurethane onto which a fine coating of graphite has been air-blown. This is then immersed in a cold plating bath, where nickel is laid down at the rate of 4 μm/h until a uniform layer of about 1.5 mm or 0.060 inch thickness has been built onto the pattern surface. Hot plating techniques lay nickel at the rate of 10 to 20 μm/h, but produce a coarse-grained porous surface. Normally this surface is dull and cannot be polished. The electroformed nickel mold produced by hot plating has about half the toughness of the cold plated electroformed nickel mold. Electroformed nickel molds are used where extreme detail is required, as with plastisol PVC for doll parts. A typical example is shown in Figure 5.5.

Figure 5.5 Electroplated nickel mold of mannequin head, courtesy of Queen's University, Belfast

5.2 Mechanical and Thermal Characteristics of Mold Materials

It is apparent from Table 5.1 that the thermal conductivities and stiffness properties of common rotational mold materials vary greatly. The question naturally arises, "How does one make comparisons because the materials will have different thicknesses depending on whether we compare them mechanically or thermally?"

5.2.1 *Equivalent Mechanical Thickness*

Consider first the mechanical equivalence. That is, what thickness does each material need to have to behave in the same way when a particular loading is applied? Consider the common loading situation of bending. In order to achieve equivalence in different materials, the product of modulus, E, and second moment of area (or moment of inertia), I, must be the same for each material. For two materials A and B, this means that

$$(EI)_A = (EI)_B \tag{5.1}$$

$$E_A \left(\frac{b_A \, d_A^{\,3}}{12} \right) = E_B \left(\frac{b_B \, d_B^{\,3}}{12} \right) \tag{5.2}$$

where b and d are the width and thickness of the cross-section of each material. If we assume that the width of each material is the same, then the thickness of material B needed to do exactly the same job as the material A is given by

$$d_B = d_A \sqrt[3]{\frac{E_A}{E_B}} \tag{5.3}$$

The four mold materials listed in Table 5.1 are compared in terms of their mechanical equivalence in Figure 5.6. Aluminum is taken as the base material and the thickness of the other materials that would be needed to provide the same flexural stiffness could be read from the graph. For example, 7-mm thick steel and 7.3-mm thick nickel are mechanically equivalent to 10-mm thick aluminum.

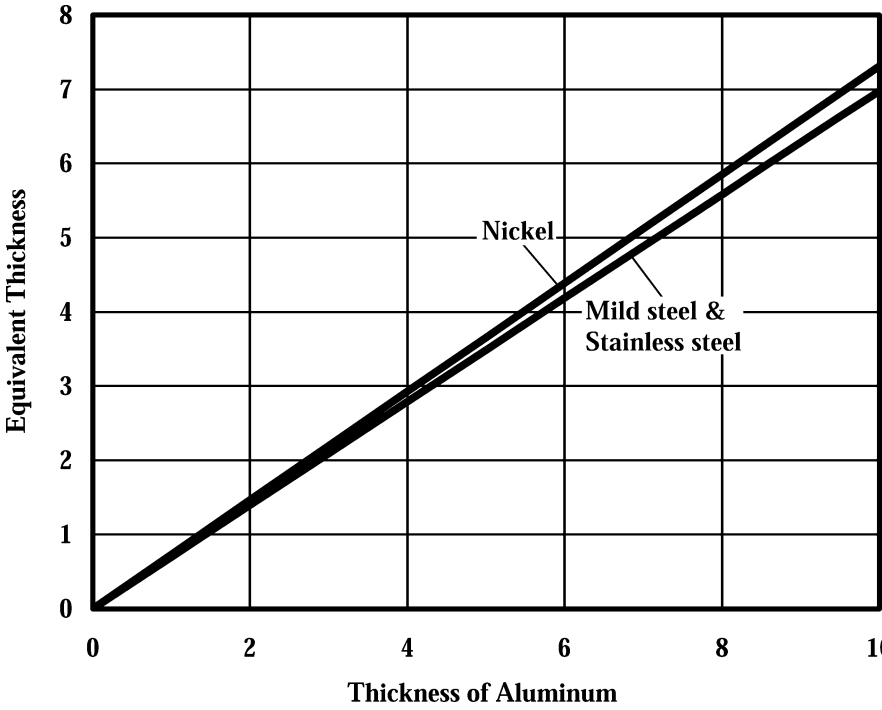


Figure 5.6 Equivalent mechanical thickness for mold materials, used with permission of The Queen's University, Belfast

5.2.2 *Equivalent Static Thermal Thickness*

Consider now the relative heating efficiencies of these materials. The heat transfer rate, Q, through a material is given by:

$$Q = UA\Delta T \tag{5.4}$$

where A is the area exposed to the heat transfer, ΔT is the temperature difference, and U is a thermal transmittance coefficient. Assuming A and ΔT are the same in all cases then U may be expressed in terms of the thermal conductivity, K, and the thickness, d, as

$$U = \frac{K}{d} \tag{5.5}$$

The different thicknesses of each material are now compared for the same static heat transfer load. This yields an equivalent thermal thickness of each material. These are shown in Figure 5.7. An alternative way to look at

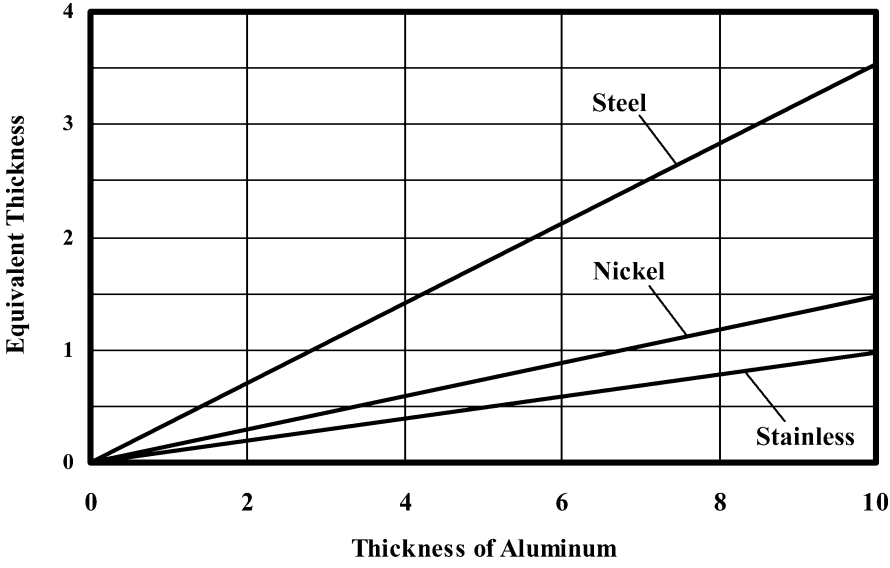


Figure 5.7 Equivalent thermal thickness of mold materials, used with permission of The Queen's University, Belfast

this is given in Figure 5.8, where the thickness of each material to give the same heat flow rate can be seen directly. For example, 5.9-mm thick aluminum, 2.07-mm thick steel, 0.87-mm thick nickel, and 0.58-mm thick stainless steel will all conduct 25 units of heat. Table 5.4 summarizes the mechanical and thermal equivalent thickness values for the different mold materials.

Table 5.4 Mechanical and Thermal Equivalent Thicknesses for Mold Materials (Relative to Aluminum)

Mold Material	Mechanical Equivalent Thickness	Thermal Equivalent Thickness	
		static	transient
Aluminum	10	10	10
Carbon Steel	7.0	3.5	6.7
Nickel	7.3	1.5	6.9
Stainless Steel	7.04	1.0	6.6

From Table 5.4 it can be seen that a 10-mm thick aluminum mold is structurally equivalent to a 7-mm thick sheet steel mold. However, sheet steel molds are usually made from 16 gage steel (1.6 mm thickness), which means that the sheet steel mold will not be as stiff as the aluminum mold, but it will

have better heat transfer under static conditions — because the thermal equivalent thickness of the steel is 3.5 mm. A thinner steel mold will therefore transfer heat more quickly than the aluminum mold.

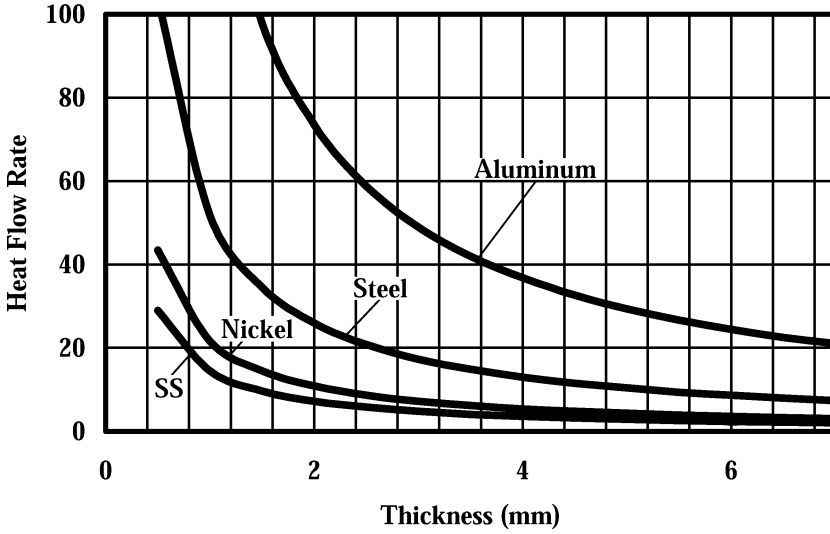


Figure 5.8 Comparison of mold materials, used with permission of The Queen's University, Belfast

5.2.3 *Equivalent Transient Thermal Thickness*

In practice, static heat transfer is not as important as transient heat transfer. According to transient heat conduction theory, the heating rate is given as:

$$\frac{T_a - T}{T_a - T_0} = e^{-\frac{h\alpha t}{Kd}} \tag{5.6}$$

as discussed earlier. The key terms are the heat transfer coefficient, h, the thermal diffusivity, α, the mold wall thickness, d, and time, t. The mold material property ratio, α/K, together with the mold wall thickness, is the proper relationship needed to determine thermal equivalence. Now, α, the thermal diffusivity is given as:

$$\alpha = K / \rho C_p \tag{5.7}$$

where ρ is density, C_p is heat capacity, and K is thermal conductivity. For equivalence of transient heat transfer therefore the conditions that must be matched are

$$(\rho\, C_p\, d)_A = (\rho\, C_p\, d)_B \tag{5.8}$$

It is surprising that the thermal conductivity does not appear in this transient equivalence relationship. The equivalent thickness for each of the mold materials in transient heat transfer is given in Table 5.4. It is apparent that the nonaluminum molds must be about 60% of the thickness of aluminum molds for the same time-dependent thermal response during heating and cooling, but it is also apparent that the reduction in wall thickness for nonaluminum molds does not need to be as severe as indicated by using the static thermal equivalence described earlier. A 7-mm thick steel mold will therefore match the strength of a 10-mm thick aluminum mold and will only have a slightly inferior transient heat transfer performance.

A comparison of the heating characteristics of typical aluminum and steel molds in a rotational molding oven is given in Figure 5.9.

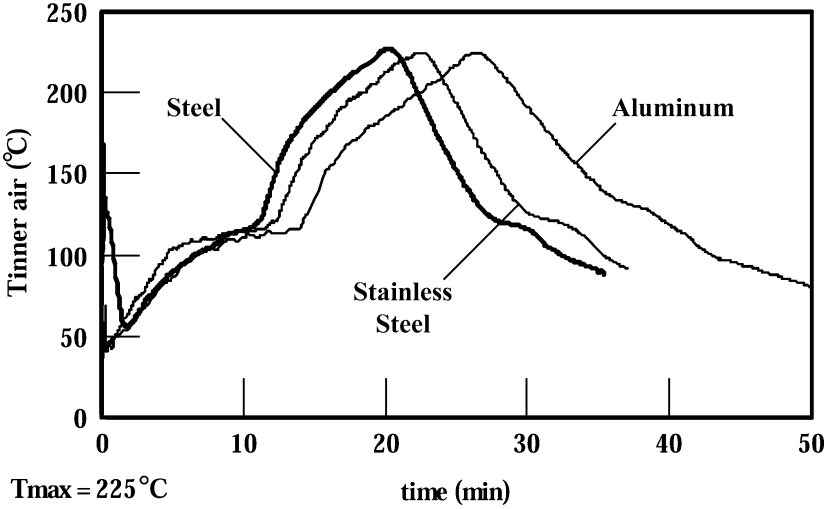


Figure 5.9 Time-dependent temperatures for heating various types of molds, used with permission of The Queen's University, Belfast

5.3 Mold Design

It is not possible to wholly separate mold design and part design. Those aspects of the design that are related mostly to mold characterization are discussed here. The technical aspects of part design are discussed in Chapter 7. A more extensive, practical treatment of part design is given elsewhere.[2]

5.3.1 *Parting Line Design*

Rotational molds usually open in a clamshell fashion for servicing. Most molds are comprised of two pieces. Three- and four-piece molds are used when the part is extremely complex or has substantial undercuts. The interface between mold sections is called the *parting line*. For simple parts such as tanks, the parting line is usually planar. For heavily contoured parts such as toys, gasoline tanks, and ducts, the parting line may be highly nonplanar. The integrity of the parting line is important to rotational molding. Mold sections must remain mated without in-plane or vertical shifting during the heating and cooling cycle. Even minute amounts of differential shifting can cause blowholes in the part along the parting line. And this integrity must remain integral throughout the life of the mold part. There are three common parting line designs for conventional rotational molds and one for pressurized molds.

5.3.1.1 *Butt or Flat*

As shown in Figure 5.10, the parting line is defined as the right-angle mating of the vertical walls of the mold halves. The mating lips or flanges are added by welding steel or are cast in for aluminum molds. It is most important that the mating flanges be as short and thin as practical, since this extra metal acts as a heat sink during heating and a hot region during cooling. Registration of the parting line location is usually accomplished with alignment pins or keys spaced every 150–300 mm (6 to 12 inches) along the periphery of the flanges.

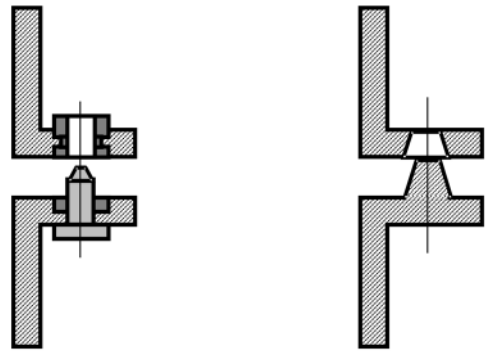
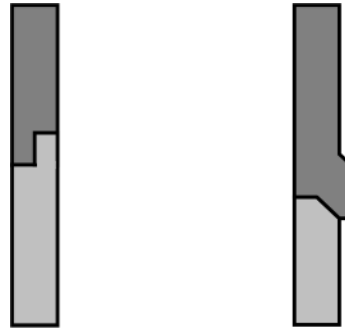


Figure 5.10 Butt or flat parting lines, used with permission of The Queen's University, Belfast

5.3.1.2 *Lap Joint*

This is also called "recess and spigot" in Europe. Figure 5.11(a) shows the common right-angle lap joint. Figure 5.11(b) shows the chamfered lap joint, which is more expensive but has lower maintenance problems and provides more readily defined seating during mold closure. Typically, this type of parting line is achieved by machining the appropriate mating edges into the cast or welded mold body. For nonplanar parting lines, the lap joint sections are cast into the aluminum mold body, with manual finishing to ensure intimate mating. Grooves are frequently added at the corners of this type of parting line closure, since powder tends to accumulate here, requiring frequent cleaning attention. And mating edges are usually chamfered to minimize mold half interference during mold closure. As with the flat parting line closure, care must be taken in designing lap joint closures, since excessive metal in the flange area can alter the heating and cooling conditions in the parting line region.

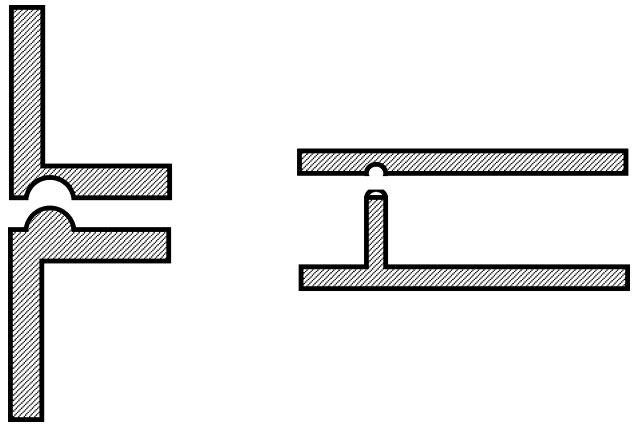


(a) Right-angle lap joint (b) Chamfer lap joint

Figure 5.11 Two types of lap joints, used with permission of The Queen's University, Belfast

5.3.1.3 *Tongue-and-Groove*

This is the most common form of parting line (Figures 5.12(a) and 5.12(b)). It is also the most expensive parting line closure to manufacture and maintain, particularly if the parting line is nonplanar. Again, grooves are added at the corners of this type of parting line closure to minimize the effect of built-up or caked sintered powder. Since the tongue-and-groove closure is self-seating, it provides the most accurate form of closure.



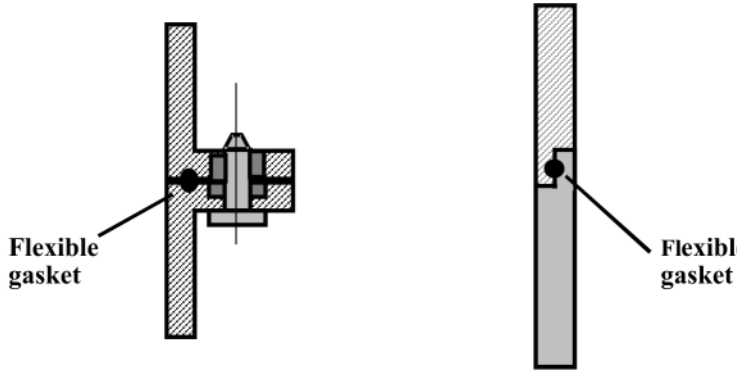
(a) Standard Tongue-and-Groove

(b) Right-Angle Tongue-and-Groove

Figure 5.12 Two types of tongue-and-groove joints, used with permission of The Queen's University, Belfast

5.3.1.4 *Gaskets*

The growing interest in pressurized molds has led to the development of gasketed parting lines, as illustrated in Figure 5.13. In the case of the butt closure, with pins or keys, the parting line now includes a gasket groove. An even better design is the sealed lap joint shown in Figure 5.13(b),



(a) (b)

Figure 5.13 Parting lines sealed with flexible gaskets, used with permission of The Queen's University, Belfast

because the mold has the opportunity to expand a little under the internal pressure, without losing the seal efficiency. Indeed the internal pressure helps maintain the seal by compressing the gasket rather than breaking the seal, as in the butt joint. Viton™ has been found to be a very suitable as a gasket material due to its durability and its retention of flexibility at oven temperatures. Teflon™ (PTFE) reinforced with Aramid™ fibers, is also used for higher temperature molding.

When rotational molding very fluid plastics, it can also be beneficial to seal the mold. Neoprene™ is one the least expensive polymeric gasketing materials available for molding EVA and vinyl plastisol. In most

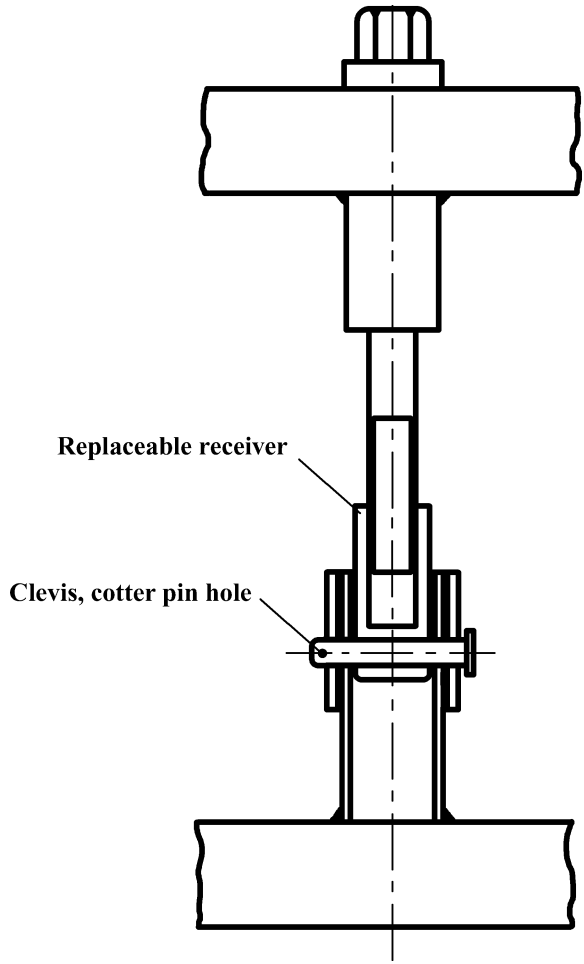


Figure 5.14 Bolt and replaceable receiver, courtesy of Kelch, USA

cases, the cost of frequent gasket replacement must be included in the cost of the molded part.

5.3.2 *Mold Frame*

It is common practice to mount mold halves in frames, as seen in Figure 5.2. This ensures that all forces are placed against the frames, not the mold shell, during assembly of the molds after filling and during disassembly after cooling. There needs to be a trade-off in attaching the mold to the frame, however. It is apparent that the mold is held more securely to the frame with many attachment points on the mold. Unfortunately, each attachment point represents a heat sink during mold assembly heating and a hot spot during cooling. One compromise is to provide many attachment points with dimensions as small as possible, particularly where the attachments contact the mold surface. Another possibility is to provide attachment points on peripheral portions of the parting line flanges, where there is little additional chance of altering the heat transfer to the sintering powder or cooling melt. Angle iron, H-channel, rectangular channel, and hollow square section tube steel are the common shapes used for mold frame construction. The mold frame halves are commonly aligned using bolts and receivers (Figure 5.14). It is recommended that both the bolt and the

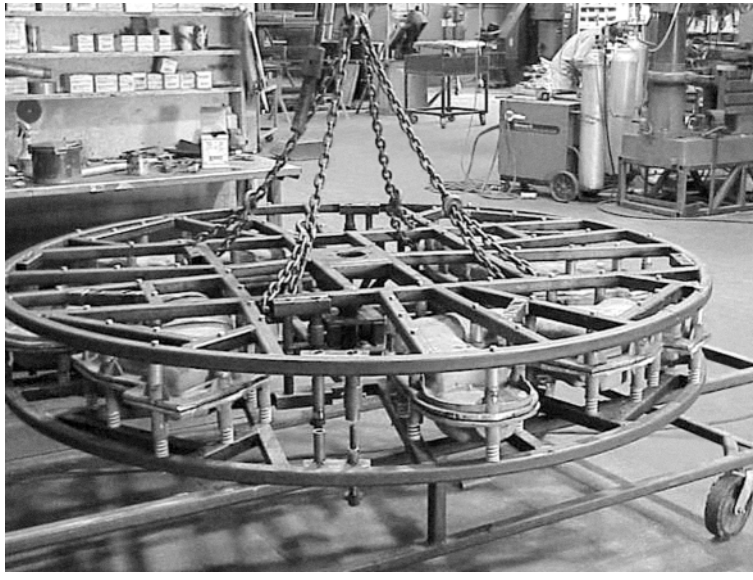


Figure 5.15 Multiple molds mounted on spider, courtesy of Lakeland Molds, USA

receiver be of hardened steel and that they be replaceable. In some cases multiple molds are mounted in a *spider* as shown in Figure 5.15.

5.3.3 *Clamping*

The mold halves must be clamped closed to minimize differential shifting due to thermal expansion. In order to minimize parting line damage that can occur when clamping bolts are aggressively tightened, molds are typically spring-mounted to the mold frame, with spring compression adjusted with a threaded bolt that is cast or welded into a noncritical section of the mold body (Figure 5.16).

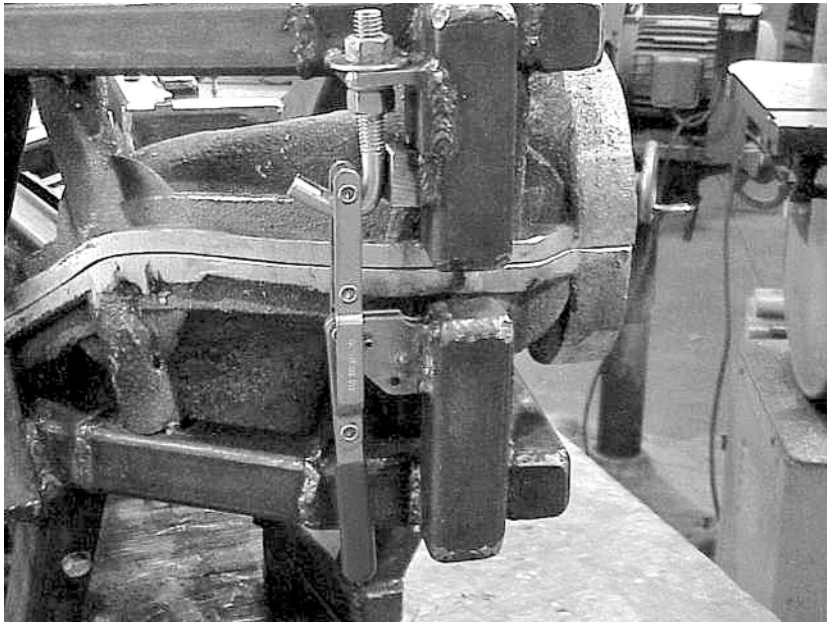


Figure 5.16 Typical mold clamping arrangement, courtesy of Lakeland Molds, USA

There are two common clamping devices. The cam clamp applies clamping force by shortening the distance between the two mold halves through an eccentric or cam linkage (Figure 5.17). The J-clamp draws the mold halves closed by looping the shaft over an adjustable J-bolt, then shortening the distance by mechanical linkage (Figure 5.18). Note that the opposing ends for these clamps are welded or bolted to the mold frames, not the mold halves themselves. Manual clamps, known as C-clamps and Vise-Grips™, can be

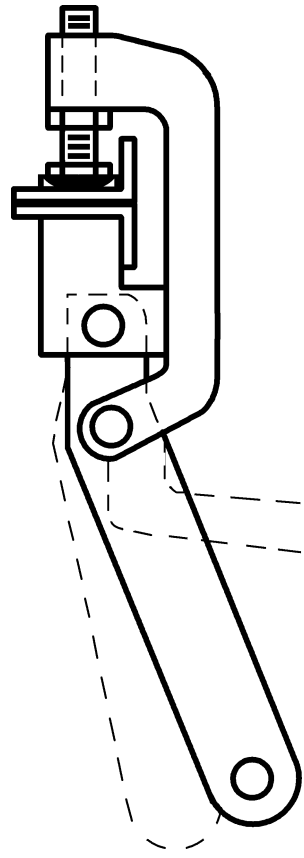


Figure 5.17 Reverse action toggle clamp, courtesy of Kelch, USA

used in temporary instances, but usually clamp directly on the parting line flanges and when misused, can damage the parting line. More often than not, the clamping force of these clamps decreases substantially during the heating portion of the process cycle. It is common knowledge that the common storage place for these manual clamps is in the bottom of the oven. For small molds and cylindrical molds that are end opening, a single clamp having interlocking fingers, similar to that for a pressure cooker lid closure, allows for very rapid mold servicing.

5.3.4 *Pry Points*

Prying is one of the most common methods of opening molds. It is also one of the most common methods of damaging mold parting lines and mold edge finishes. Pry points welded to the mold frame sections mini-

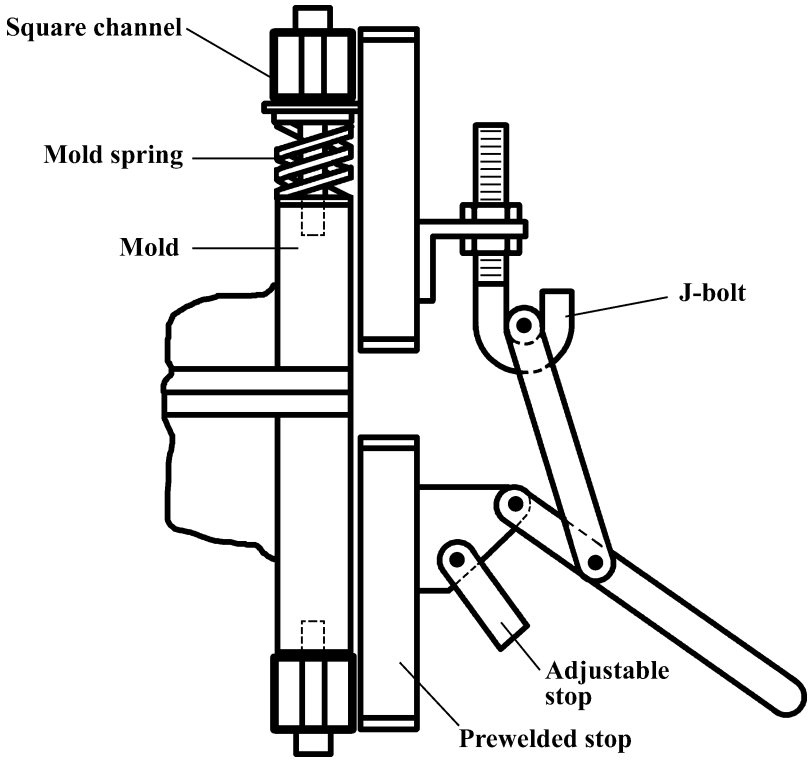


Figure 5.18 J-bolt mold clamping arrangement, courtesy of Kelch, USA

mize this type of damage. Special mechanical jacks, similar to car jacks, should be used to improve mold opening efficiency. These are either permanently mounted to the mold frame or are manually inserted between pry points during mold servicing.

5.3.5 *Inserts and Other Mechanical Fastening Methods*

Frequently, plastic parts need to be fastened to other assemblies. Some common fastening methods are discussed here.

5.3.5.1 *Self-tapping Screws*

There are two general types of self-tapping screws. Thread-cutting screws cut through the polymer and are used primarily with tough or ductile-tough polymers. Thread-forming screws push the polymer away from the cutting surface and are used primarily with softer polymers such as polyethylenes and polypropylene. These screws are inexpensive and allow for

very rapid assembly. The screw holding power is low and disassembly and reassembly usually leads to damage of the formed thread. These screws can crack or chip brittle plastics.

5.3.5.2 *Mechanical Fastening*

A common method of mechanical fastening involves drilling a hole completely through the part wall. A metal fastener in a receptor is then inserted through the hole, and secured with a mechanical collar. These assemblies are expensive, but the holding power is high. There is relatively little stress in the polymer due to the fastening forces and disassembly and reassembly is easy, with little damage to the polymer. This type of fastening requires access to the inside of the molded part.

5.3.5.3 *Postmolded Insert*

There are many types of postmolded inserts. In certain instances, an insert can be pressed into the molded part when it is still hot or the insert can be heated and pressed into the cool molded part. The latter is a common way of inserting fasteners in polyethylene and polypropylene. Installation is simple but holding power is limited and reliability is questionable. Alternatively, an insert can be glued in place. Ultrasonic welding and spin welding are also very effective. In both cases, the polymer is locally melted during insertion of the fastener. These fasteners are relatively expensive and require special equipment, but the holding power is high, and there is little stress in the polymer region around the insert. Expansion inserts are used when the polymer wall is thick and the polymer is ductile-tough or just ductile. These inserts are expensive, but installation is simple.

5.3.5.4 *Molded-in Insert*

Molded-in inserts are affixed to the mold surface during the mold servicing stage in the cycle. The method of holding the insert depends to a great degree on the size, number, and function of the insert. There are two general classes of molded-in inserts. *Plastic inserts* are used where the dimensional tolerance of a rotationally molded region is unacceptable, or where rotational molding is impractical due to wall thickness or mold dimensions. One classic example is tank access, where a threaded spout or bung must mate with metal or another plastic fitting. Another is where the inside dimension of the molded part must be precise, as with pipe fittings such as elbows, tees, and Ys. In this case, an injection molded plastic

insert is affixed to the mold surface during servicing. Care must be taken during the rotational molding process to minimize thermal damage and heat distortion to the insert while ensuring that there is sufficient fusion of the sintered and molten polymer to the insert to provide integrity in the molded part. Typically, the critical portions of the insert are thermally insulated, while the regions for fusion are exposed. Molding with plastic inserts requires lower oven temperatures and longer cycles than normal, and usually there are several iterations on the insert design before adequate fusion at the interface is achieved.

Metal inserts are usually classified as ferrous or nonferrous. Ferrous metal inserts can be affixed to the mold surface with magnets. Nonferrous inserts require mechanical means for holding them in place. If the inserts are in the direction of part pull from the mold, they can be simply pressed onto tapered pins. If the inserts are not in the part pull direction, they and their affixing methods represent undercuts. Any mechanical method of holding them in place must be disengaged prior to part removal. In order to improve pullout strength for metal inserts, they should be designed with large-dimensioned flanges that extend parallel to the mold wall (Figure 5.19). As shown, the flanges should be triangular or square and not round, to minimize spinning of

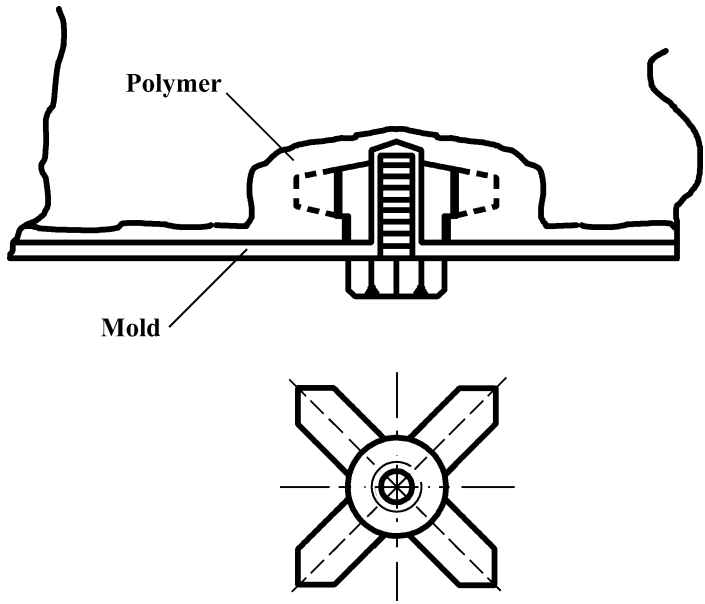


Figure 5.19 Flanged metal insert, used with permission of The Queen's University, Belfast

the fastener. Ganged inserts are used if many inserts are required. If the insert-to-insert spacing is critical, the inserts are mounted on an open metal grid that is then affixed to the mold wall.

5.3.6 *Threads*

Molded-in threads are problematical in rotational molding. External threads on the molded part are difficult. In recent years, wipe-on coatings have been developed to improve heat transfer in external thread areas (Figure 5.20). Internal threads on the molded part are possible but thread design is extremely important, since the powder must flow uniformly into the thread base. Typically, the insert represents a heat sink and an obstacle during powder flow. The backside of the obstacle sees less powder and tends to be more porous than the side facing the powder flow. As with any obstacle in the mold, reversal of rotation can alleviate the problem, but this must be done at the appropriate time in the cycle. If rotation reversal is too early in the cycle, it has no effect. If it is too late, the majority of the powder has already stuck to the mold surface, and it again has no effect.

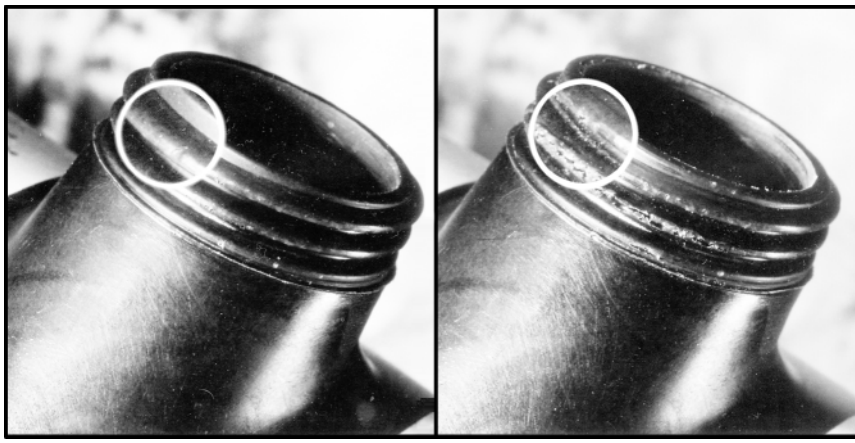


Figure 5.20 Use of coatings to improve thread detail, courtesy of Mold-In Graphics, USA

The thread-forming insert can be made of bronze, phosphor bronze, brass, or beryllium-copper to improve its heat transfer. If the thread dimension is large, the insert can be cored out, as shown in Figure 5.21. Preferably, threads should be of short length and of large diameter to facilitate good heat transfer. For short length threads, pitch is not critical, since the inserting component will correct any inaccuracy in pitch. Thread shape is critical, on the other

hand, since differential shrinkage during cooling will distort thread shape. If the distortion is severe, thread shear and stripping will occur when the mating threaded component is inserted. It is recommended that a plastic insert be used for long length threads.

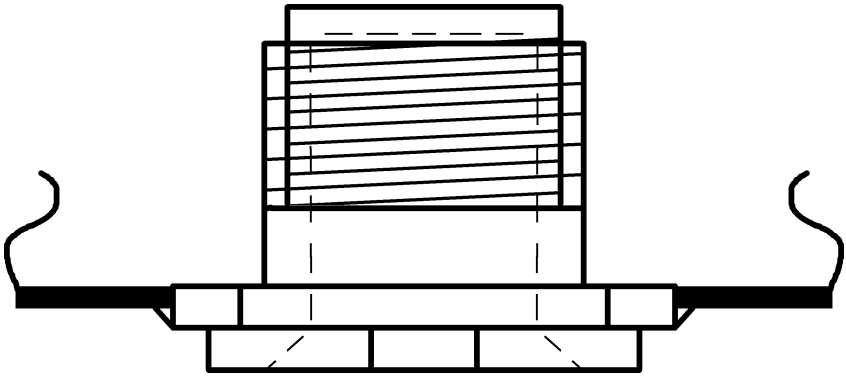


Figure 5.21 Removable thread element, courtesy of Kelch, USA

5.3.7 *Cut-out Areas*

In the majority of cases, the powder flows uniformly over the entire mold surface. If a region of the molded part is to be cut out to gain access to its inside surface, the region is saw (or router) cut, as described in Chapter 7. To minimize the material that must be removed, an insulating blanket, typically of nonporous cement-board or Teflon™, is placed over the appropriate region. The use of nonwoven fiberglass mat is not advised, since it adsorbs water during the cooling cycle and retains it into the oven cycle, where the water becomes steam.

5.3.8 *Kiss-offs*

Kiss-offs are used to provide rigidity in the rotationally molded part. As the name suggests, they are a means of attaching opposite faces of the hollow part in order to provide better flexural stiffness (Figure 5.22). Shallow kiss-offs are made of highly conducting metal such as copper and may be attached to the mold surface as inserts. In shallow kiss-offs, baffles mounted on the mold wall are effective. Large dimensioned kiss-offs are designed directly into the fabricated or cast mold. The air flow amplifier described in Chapter 4, or heat pipes can be used to force hot oven air into the deeper large kiss-offs.

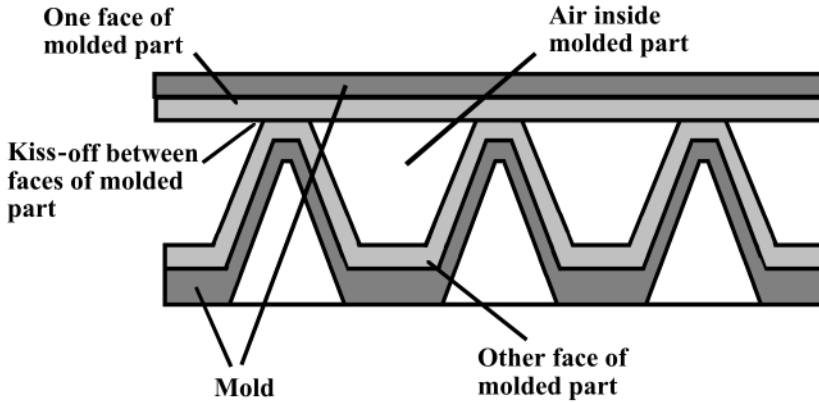


Figure 5.22 Kiss-off feature in rotationally molded part, used with permission of The Queen's University, Belfast

5.3.9 *Molded-in Handles*

To provide handles in parts, tubes, pipes, rectangular channels, and other hollow shapes can be molded into the part simply by extending the shape completely through the mold walls. If the shape surface is roughened, some adhesion of the plastic onto the handle is possible. If plastic must uniformly coat the handle, oven air must be positively directed down the inside of the shape. If a pass-through hole is needed, rather than a molded-in handle, the shape should be of insulative material. Of course, provision must be made for parting the mold at the handle.

5.3.10 *Temporary Inserts*

Frequently, parts must contain company logos, information panels, and production dates. These inserts are usually temporarily fixed through an appropriate access in the mold wall. In some cases where texture is to be changed locally, for example, entire side-wall panels may be made as temporary sections. Heat transfer to these temporary inserts should be the same as that to the surrounding mold material, to minimize changes in wall thickness. Furthermore, the temporary insert must fit tightly against the surrounding mold material to minimize blowholes at the insert edges. Press-in inserts are normally unacceptable.

Next Page

Previous Page

5.4 Calculation of Charge Weight

A fundamental part of manufacturing a product by rotational molding is relating the part wall thickness to the shot, or charge weight. In some cases, the weight will be fixed to make the end product economically viable. The wall thickness may then have to be calculated in order to do a quick (or thorough) stress analysis to ensure that the end product will perform its function. In other cases, the desired wall thickness will be known, perhaps from a finite element analysis, and the appropriate charge weight must be estimated to provide this thickness. If the mold has been designed using a CAD system or manufactured using a CNC-driven cutter, the surface area of the part will be known. From this, part wall thickness can be obtained and hence, an accurate charge weight determined.

If the end product has an irregular shape it is not easy to calculate accurately the desired weight or wall thickness. The rotational molder must then rely on experience or trial-and-error to get the correct charge of powder. This can be time consuming and wasteful of material, so it is often worthwhile to make some attempt at estimating the amount of powder needed for a new molding. Usually this involves simplifying the shape of the mold so that a quick approximation for shot weight can be made.

5.4.1 *Methodology*

Except for scrapped parts or cut-out sections, there is no waste material in rotational molding. All of the material that goes into the mold contributes to the shape of the end product. There may be some trimming afterwards but a fixed weight of material is charged to the mold to make the shape of the hollow part.

To get the charge weight for a desired wall thickness, it is simply necessary to work out the volume of material in the end product and multiply this by the density of the plastic. The volume of the plastic is obtained by taking the volume of the inside of the mold and subtracting the volume of the air space inside the plastic part. For a molded cylinder of outside diameter D, length L, and wall thickness h, as shown in Figure 5.23, this approach would give a charge weight of

$$W = \rho\left[\frac{\pi D^2}{4}L - \frac{\pi(D-2h)^2}{4}(L-2h)\right] \tag{5.9}$$

where ρ is the density of the solid plastic. This equation will give the charge weight for any desired wall thickness, assuming the other outside dimensions of the cylinder are known. However, it is difficult to solve by any method other than an iterative method, to give the wall thickness, h,

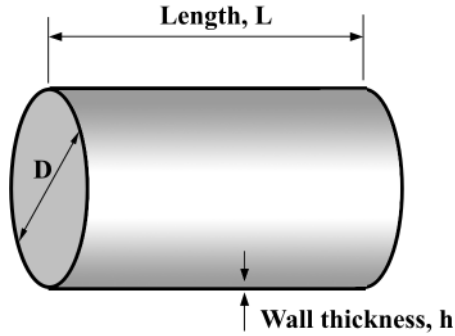


Figure 5.23 Cylindrically molded part, used with permission of The Queen's University, Belfast

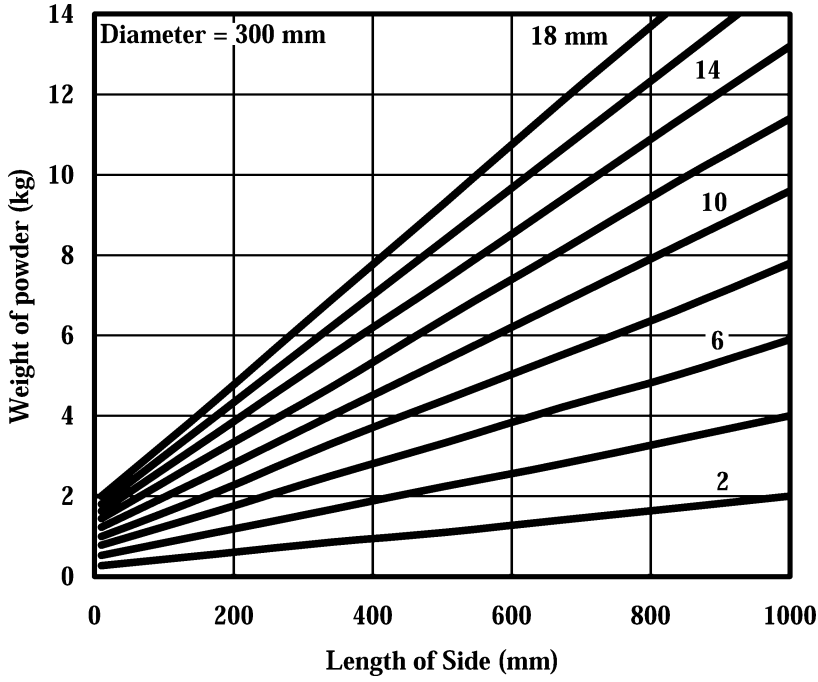


Figure 5.24 Weight of powder needed for cylindrical parts, used with permission of The Queen's University, Belfast

for a given charge weight. Therefore the best way to use the equation is in the form of the charts that can be created from it.

Figure 5.24 shows the weight of powder (solid density = 930 kg/m^3) needed to produce a given wall thickness in cylindrical molded parts of known outside dimensions. For example, to produce an 8-mm thick cylinder with a diameter of 300 mm and 1000 mm long requires 8 kg of powder. This chart has been produced for a plastic with a density of 930 kg/m^3. The weights for other densities are simply obtained by multiplying by the new density divided by 930. In most cases this correction will be very small and is usually not necessary.

Although Figure 5.24 is for a cylindrical shape, it could also be used for any mold shape that can be approximated to a cylinder. To assist with such extrapolations, Figure 5.25 shows charge weights for a rectangular box-shaped part. As there are many permutations of sizes of such parts, only one typical geometry is considered. Figures 5.26 is for a rectangular box in which the ends are also rectangular with the long side equal to twice the short side.

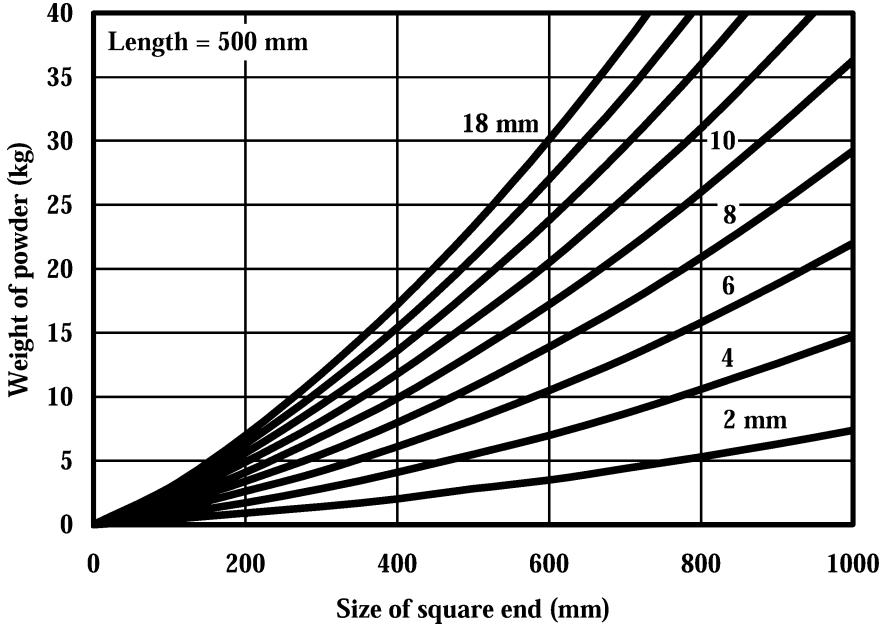


Figure 5.25 Weight of powder for rectangular part with square ends, used with permission of The Queen's University, Belfast

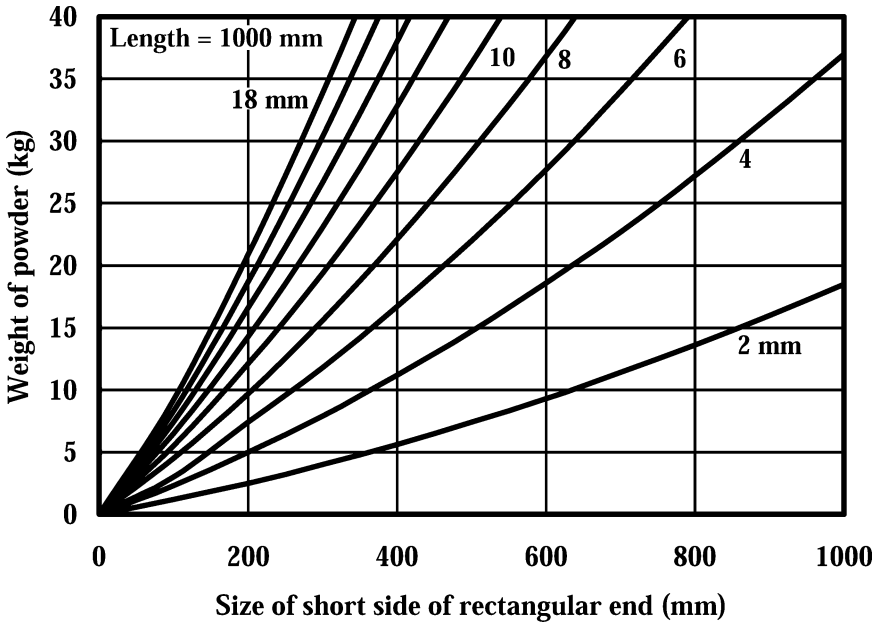


Figure 5.26 Weight of powder for rectangular part with rectangular ends, long side = twice short side, used with permission of The Queen's University, Belfast

It was indicated above that it could be difficult to calculate the wall thickness from a known charge weight because the equations for most part shapes are difficult to rearrange to get an explicit expression for wall thickness. An alternative way to estimate the wall thickness is to take the volume of the part as the surface area of the inside of the mold multiplied by the wall thickness of the part. The charge weight is then given by the following equation:

$$\text{Weight of plastic} = \text{Surface area of molding} \times \text{thickness of molding} \times \text{density of plastic} \quad (5.10)$$

This equation can then be easily rearranged to give the wall thickness. This approach assumes that the wall thickness of the plastic part is uniform. There is also an inaccuracy in this simple approach in that, as the plastic builds up on the inside of the mold, the surface area available to the remaining material is changing. In most cases it is decreasing so that for a particular charge of material, the wall thickness will tend to be greater than that used to calculate the charge weight. This approach also counts several times the material in the corners of the molded part and so this

also contributes to an error that is usually about 12% for most mold shapes and part wall thicknesses.

Table 5.5 gives formulae for the volume and surface area of a variety of shapes so that the shot weight can be calculated using the more accurate method based on volumes or using the approximate method based on surface areas.

Example 5.1

Determine the charge weight of polyethylene at 930 kg/m^3 needed to rotationally mold a kayak with a wall thickness of 5 mm. The mold may be assumed to be a bicone-cylinder with the cylinder 1 m in diameter by 1.6 m long and the cone height 2 m.

Solution

From Table 5.5, the bicone-cylinder part volume is given by

$$\text{Part volume} = \pi\left[R^2 L - (R-h)^2 L\right] + \pi\left(\frac{2}{3}\right)\left[R^2 H - (R-h)^3 \frac{H}{R}\right] \quad (5.11)$$

$$\text{Part volume} = 0.056 \text{ m}^3$$

Multiplying this by the density of the plastic gives the charge weight as 52.2 kg (115 lbs).

Example 5.2

A golf cart trailer door is 2 m × 0.67 m × 0.1 m in depth. It is to be rotationally molded from polyethylene with a density of 930 kg/m^3. The part wall thickness is 9 mm. What is the charge weight and can the mold be filled? The bulk density of the polyethylene powder is 350 kg/m^3.

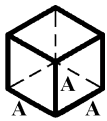
Solution

From Table 5.5, assuming that the mold is a rectangular box, the mold volume is 0.134 m^3 and the volume of the plastic in the door is given by

$$\text{Part volume} = A\,B\,C - (A - 2h)\,(B - 2h)\,(C - 2h) \quad (5.12)$$

$$\text{Part volume} = 0.028 \text{ m}^3$$

Table 5.5 Volumes and Areas for Generic Mold Shapes (part wall thickness = h)

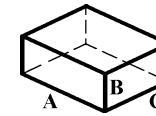


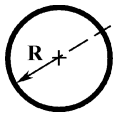
Cube (side = A)

Mold Volume	A^3
Plastic Volume	$[A^3 - (A\text{-}2h)^3]$
Mold Surface Area	$6A^2$

Rectangular box (sides *A*, *B*, *C*)

Mold Volume	ABC
Plastic Volume	$[ABC - (A\text{-}2h)(B\text{-}2h)(C\text{-}2h)]$
Mold Surface Area	$2AB + 2BC + 2CA$



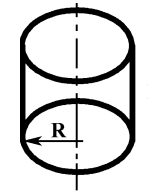


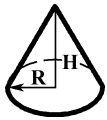
Sphere (radius, *R*)

Mold Volume	$(4\pi/3)R^3$
Plastic Volume	$(4\pi/3)[R^3 - (R\text{-}h)^3]$
Mold Surface Area	$4\pi R^2$

Cylinder (radius, *R*; height, *H*)

Mold Volume	$\pi R^2 H$
Plastic Volume	$\pi[R^2H - (R\text{-}h)^2(H\text{-}2h)]$
Mold Surface Area	$2\pi R^2 + 2\pi RH$



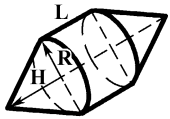


Right cone (radius, *R*; height, *H*)

Mold Volume	$(\pi/3)\,R^2H$
Plastic Volume	$(\pi/3)\,[R^2H - (R\text{-}h\text{-}Rh/H)^2\,(H\,(R\text{-}h)/R\text{-}h)]$
Mold Surface Area	$\pi R^2 + \pi R\sqrt{(R^2+H^2)}$

Right bicone (radius, *R*; height, *H*)

Mold Volume	$(2\pi/3)R^2H$
Plastic Volume	$(2\pi/3)[R^2H - (R\text{-}h)^3H/R]$
Mold Surface Area	$2\pi R\sqrt{(R^2+H^2)}$

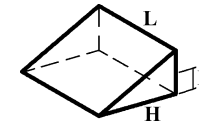


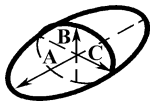
Right bicone + cylinder (radius, *R*; height, *H*; length, *L*)

Mold Volume	$\pi R^2 L + (2\pi/3)\,R^2H$
Plastic Volume	$\pi[R^2L - (R\text{-}h)^2L + (2/3)R^2H - (2/3)(R\text{-}h)^3H/R]$
Mold Surface Area	$2\pi R\sqrt{(R^2+H^2)} + 2\pi RL$

Right wedge (half base, *R*; height, *H*; length, *L*)

Mold Volume	RHL
Plastic Volume	$RHL - (L\text{-}2h)\,[(R\text{-}h\text{-}Rh/H)\,(H\,(1\text{-}h/R)\text{-}h)]$
Mold Surface Area	$2RH + 2RL + LH + L\sqrt{(4R^2+H^2)}$





Ellipsoid (semi axes, *A*, *B*, *C*)

Mold Volume	$(4\pi/3)ABC$
Plastic Volume	$(4\pi/3)[ABC\text{-}(A\text{-}h)(B\text{-}h)(C\text{-}h)]$
Mold Surface Area	No simple equation

Multiplying this by the density of the plastic gives the charge weight as 26 kg (57.2 lbs). Dividing this by the bulk density of the powder gives the volume of the powder as 0.074 m^3. As the volume of half the mold is 0.067 m^3 there is insufficient room for the shot size, unless the powder is heaped up.

The best mold design would open on one 2 m × 0.67 m side.

Example 5.3

A tractor component is modeled as a wedge with a base of 0.5 m, a height of 1 m and a length of 0.33 m. It is to be made of polyethylene at 935 kg/m^3. The bulk density of polyethylene is 375 kg/m^3. Determine the maximum charge weight that could be used in this mold and the final wall thickness. Estimate the error in the method used.

Solution

From Table 5.5, the component volume is 0.083 m^3. If the volume is filled completely with bulk powder, the charge weight is 30.9 kg. Therefore the final polymer volume is 30.9/935 = 0.033 m^3. From Table 5.5, the wedge mold surface area is 1.364 m^2. The approximate thickness based on the mold surface area is about 0.033/1.364 = 0.024 m or 24 mm.

Using this thickness to calculate the part volume using the equation in Table 5.5, it is found that this is 0.025 m^3 and the part weight is 24 kg. Thus, the error in using the approximate method is about 30%.

5.4.2 *Maximum Part Wall Thickness for a Given Mold*

Another important practical point when determining the size of the charge in rotational molding is that the plastic powder has a much lower density than the solid material. This means that for a given weight, the powder will occupy a much larger volume than the solid material. A consequence of this is that some wall thicknesses will not be attainable because it is not possible to get enough powder into the mold at the outset. If we assume a typical powder bulk density of 350 kg/m^3 then it can be shown that for a 300-mm diameter cylinder with a length of 1000 mm it is possible to get wall thicknesses up to about 25 mm (1 in) without the need for a drop box. However, for the same diameter and a length of 200 mm, the maximum attainable wall thickness is about 16 mm.

Figure 5.27 illustrates the maximum wall thicknesses that are achievable in a single shot for a cylindrical shaped mold. This data has been calculated for a powder bulk density of 350 kg/m^3 and a plastic solid density of 930 kg/m^3.

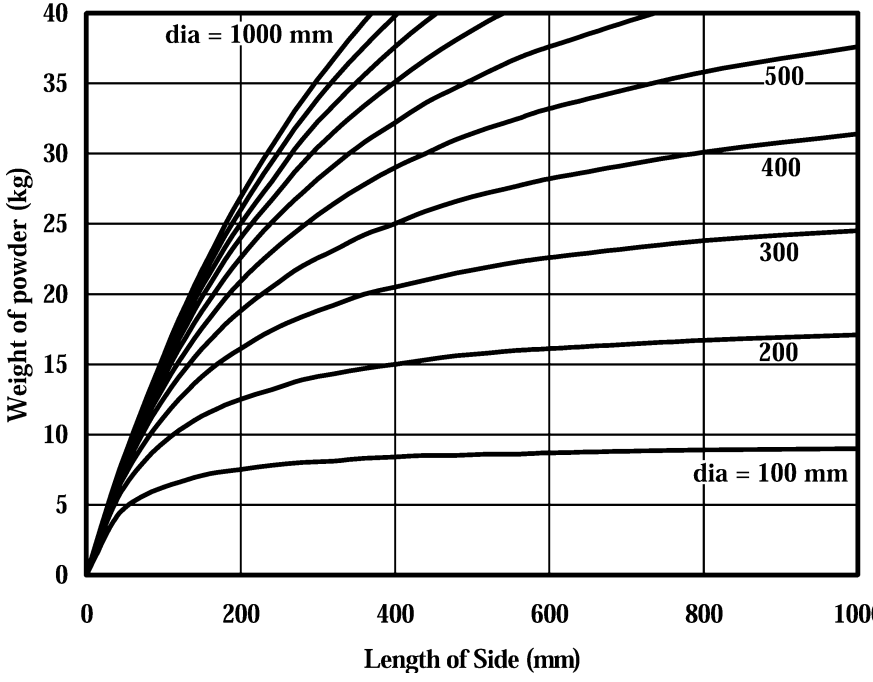


Figure 5.27 Maximum permissible wall thickness for cylindrical parts, used with permission of The Queen's University, Belfast

Always remember that it is only possible to calculate approximate values of shot sizes due to the complexity of the part shape, the variations in wall thickness, changes in material density, etc. However, a good estimate is possible in most cases and this can save quite a bit of time and money. Information on shot size calculation is also available on a CD available from the Association of Rotational Molders.

Example 5.4

A hollow rectangular box has a length of 1 m and the ends are 100 mm × 200 mm, as shown in Figure 5.28. If it is to be rotationally molded from polyethylene with a density of 930 kg/m^3, what is the maximum wall

thickness that can be produced with one charge of material? The bulk density of the powder is 350 kg/m^3.

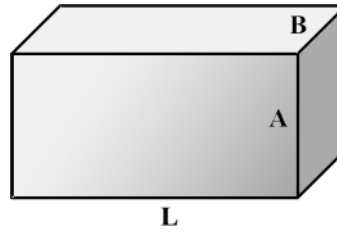


Figure 5.28 Hollow rectangular box molding, used with permission of The Queen's University, Belfast

Solution

The maximum weight of powder that can be put in the mold is:

$$Wt_{\text{powder}} = \rho_B \times A \times B \times L \tag{5.13}$$

The weight of the molded part is:

$$Wt_{\text{part}} = \rho_P \times [(A \times B \times L) - (A - 2h)(B - 2h)(L - 2h)] \tag{5.14}$$

As there is no material lost in rotational molding, these two weights must be equal. In theory, therefore, we can equate the weight of the powder to the weight of the molded part and solve for the thickness, h. In practice, this equation is difficult to solve by methods other than iterative procedures.

As an alternative, the weight of the molded part can be approximated by the equation:

$$Wt = \rho_P \times h \times [(2 \times A \times B) + (2 \times B \times L) + (2 \times A \times L)] \tag{5.15}$$

Thus, by letting $A = 2B$ as given in the question, we can write the wall thickness, h as:

$$h = \frac{B \times L \times \rho_B}{[(2 \times B) + (3 \times L)] \times \rho_P} \tag{5.16}$$

From the data given in the question we can then calculate the maximum permissible wall thickness as $h = 11.8$ mm. The error in this approximate solution is generally about 12%. If one compares the weight of powder to the

calculated weight of the part using this value of h, the latter is always less because in the approximate solution there is some double counting of material in the corners. Nevertheless, the method is sufficiently accurate for most purposes and as the error is almost constant for all sizes of molds, it can easily be allowed for.

The more general equation for a rectangular box of length, L, where the long end side is 'x' times the short end side, B, is given by:

$$h = \frac{xBL\rho_B}{2\left[xB + (x+1)L\right]\rho_P} \tag{5.17}$$

5.5 Venting

It is normal on a rotational mold to have a vent port to allow air to leave the mold during the heating stage and enter the mold during the cooling stage. This is because the pressure in the mold cavity must be controlled throughout the heating and cooling process. If the mold were completely sealed, then the gas trapped in the mold would want to expand when it is heated. However, this would not be possible because of the constraints of the mold, and so a pressure would build up inside the mold. If this happens during molding, it is possible that molten plastic will get forced out at the parting line causing a blowhole in the part or, in severe cases, the mold may distort.

It is possible to calculate the pressure build-up as follows. The ideal gas law may be used to determine the effect on pressure of increasing temperature when the mold is not vented:

From the ideal gas law, we know that

$$P\,V = n\,R\,T \tag{5.18}$$

where n and R are constants. If V is treated as a constant, the pressure is proportional to T. Considering the state of the gas before and after the temperature change, the following obtains:

$$\begin{aligned} P_1\,V &= n\,R\,T_1 \\ P_2\,V &= n\,R\,T_2 \end{aligned} \tag{5.19}$$

or

$$\frac{P_1}{T_1} = \frac{n\,R}{V} \tag{5.20}$$

$$\frac{P_2}{T_2} = \frac{n\,R}{V}$$

Since both P_1 / T_1 and P_2 / T_2 equal nR / V, by the transitive property, they must be equal to each other:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \tag{5.21}$$

Hence the final pressure at the elevated temperature is given by the Gay-Lussac law:

$$P_2 = \left(\frac{P_1}{T_1}\right) T_2 \tag{5.22}$$

Example 5.5

A rotational mold is in the shape of a cube with each side 1 m long. If the vent tube is completely blocked, calculate the opening force generated in the mold as it is heated from 25°C to 200°C. If there is a second mold on the plate of the machine, also cube shaped with sides 0.5 m, calculate the opening force in this mold if its vent tube is also blocked.

Solution

For the 1 m^3 mold, the new pressure, P_2 at the higher temperature is calculated by using the Gay-Lussac law.

First, the temperatures are converted to absolute temperatures (K):

$$T_1 = (25 + 273) = 298 \text{ K}$$

$$T_2 = (200 + 273) = 473 \text{ K}$$

Then, by the Gay-Lussac law, with an initial pressure of 1 atmosphere, the new pressure is:

$$P_2 = P_1\left(\frac{T_2}{T_1}\right) = (1)\left(\frac{473}{298}\right) = 1.59 \text{ atm} = 161 \text{ kN/m}^2 \ (23 \text{ lb}_f/\text{in}^2)$$

The pressure generated inside the mold is independent of the size of the mold. The force inside the mold will, of course, depend on the size of the mold because it is given by the pressure multiplied by the area on which it acts. In this case, the mold is a cube with side walls of 1 m × 1 m so the opening force on the parting line is:

$$\text{Force} = 161 \cdot 10^3 \cdot 1 = 161 \text{ kN}$$

Note that this is a substantial force. So it is not surprising that molders report that in a poorly vented mold, the internal pressure generated by the temperature rise can be sufficient to bow out or otherwise distort the sidewalls on metal molds.

If the sidewalls of the cube are 0.5 m square then the area is 0.25 m^2. The pressure in the mold remains unchanged and so the opening force is given by:

$$\text{Force} = 161 \cdot 10^3 \cdot 0.25 = 40 \text{ kN}$$

The same analysis can be used to assess a quite common practical problem, where the vent remains open during the heating stage but then becomes clogged so that air cannot be drawn into the mold during cooling. Consider the cooling case where initially the internal air temperature is 200°C and the internal pressure is 1 atmosphere. Using the Gay-Lussac law as before:

$$P_2 = P_1\left(\frac{T_2}{T_1}\right) = (1)\left(\frac{293}{473}\right) = 0.63 \text{ atm} = 64 \text{ kN/m}^2 \ (9.3 \text{ lb}_f/\text{in}^2)$$

This partial vacuum may be sufficient to draw in or otherwise distort sidewalls on thin-wall sheet-metal molds.

An alternative way to consider the venting needed in a rotational mold is to estimate the volume of air that must escape from the mold during heating or enter the mold during cooling so that the internal pressure remains at atmospheric. The volume of air to be vented out during heating and drawn in during cooling is obtained from the adaptation of the ideal

gas law, known as the Charles law. This relates volume to temperature at constant pressure in the form:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} = \text{constant} \tag{5.23}$$

So

$$V_2 = V_1\left(\frac{T_2}{T_1}\right) \tag{5.24}$$

If the pressure in the mold is 1 atmosphere at 25°C, then as the mold is heated to 200°C, the volume that the air must occupy to maintain the pressure at atmospheric is given by:

$$V_2 = V_1\left(\frac{T_2}{T_1}\right) = (1)\left(\frac{473}{298}\right) = 1.59 \text{ m}^3$$

Thus the volume of air that must be allowed to escape during heating, or re-enter the mold during cooling, is (1.59 – 1) = 0.59 m^3 per m^3 of mold volume. The vent tube must be large enough to accommodate this airflow. In general, the guideline for the size of the vent is that it should be as large as possible, but not so large as to allow powder to pass through it during the early part of the cycle. There are some quantitative "Rules of Thumb" that are used in the industry but these can vary widely in what they recommend. One of the most common rules of thumb[3, 4] is that the vent should be 0.5 inch in diameter for each cubic yard of mold volume (or 13 mm for each 1 m^3 of volume). However, there is a basic flaw in this guideline because it is implied that if the volume of the mold is doubled then the diameter of the vent tube should be doubled. In fact, if the volume of the mold is doubled, it is the area of the vent tube that should be doubled, not the diameter. In such circumstances, the diameter should increase by 1.414. Also, the above guideline tends not to work very well for mold volumes below 1 m^3.[4, 5]

5.5.1 *Simple Estimate for Vent Size*

It is not straightforward to work out theoretically the size of the vent tube for a particular mold. In the first place one is dealing with the flow of a compressible gas in a transient situation where temperature (and possibly pressure) are changing continuously. In practice many other factors, such

as the efficiency of the oven, the size of the mold, the thickness of the molded part, the integrity of the parting line, the nature of the cooling, and the length of the vent tube will also affect the venting process. Nevertheless, in order to get a rough idea of the size that a vent should be, it is possible to do a simple calculation as illustrated in the following Example.

Example 5.6

It is empirically known that for one rotational molding machine, when the oven temperature is set at 350°C, the oven time for cubic shaped molds is given by:

$$t = \left(\frac{D}{1000}\right)^{0.1} \times (h + 2h^{0.2}) \tag{5.25}$$

where the oven time is in minutes when the side of the cube, D, and the thickness of the molded part, h, are in mm. Calculate an appropriate vent tube diameter when a 1-m polyethylene cube with a wall thickness of 6 mm is molded on this machine. The mold and powder are initially at 25°C and they are heated to an internal air temperature of 200°C. The speed of the air from the vent tube may be assumed to be 2 m/s. The solid density of the polyethylene and the bulk density of the powder are 930 kg/m^3 and 350 kg/m^3, respectively.

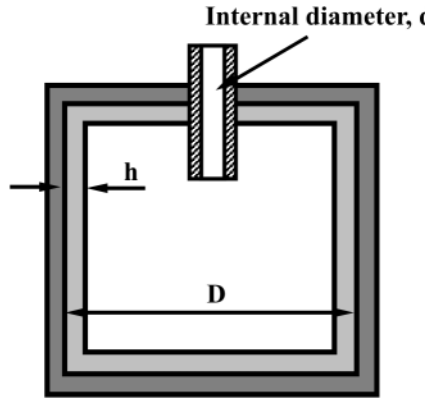


Figure 5.29 Cube mold with vent tube, used with permission of The Queen's University, Belfast

Solution

As illustrated in Figure 5.29, the volume of air inside the mold at the beginning is given by:

$$\text{Vol} = \left[D - 2\left(\frac{\rho_P}{\rho_B} \right) h \right]^3 \tag{5.26}$$

As shown earlier, when air is heated from 25°C to 200°C, there is an increase in volume of 59%. Therefore the volume of gas that flows out of the mold is

$$\text{Vol}_{\text{esc}} = 0.59 \left[D - 2\left(\frac{\rho_P}{\rho_B} \right) h \right]^3 \tag{5.27}$$

From knowledge of the oven time, the average gas flow rate from the mold is estimated. This is given by:

$$Q = \frac{0.59 \left[D - 2\left(\frac{\rho_P}{\rho_B} \right) h \right]^3}{60 \left(\frac{D}{1000} \right)^{0.1} \times (h + 2h^{0.2})} \tag{5.28}$$

Assuming that all the air passes through the vent tube, this is equal to the product of area and gas speed in the vent tube. Hence:

$$\left(\frac{\pi d^2}{4} \right) V = \frac{0.59 \left[D - 2\left(\frac{\rho_P}{\rho_B} \right) h \right]^3}{60 \left(\frac{D}{1000} \right)^{0.1} \times (h + 2h^{0.2})} \tag{5.29}$$

Rearranging this for the diameter, d, of the vent tube:

$$d = \sqrt{\frac{4 \times 0.59 \left[D - 2 \left(\frac{\rho_P}{\rho_B} \right) h \right]^3}{60 \pi V \left(\frac{D}{1000} \right)^{0.1} \times (h + 2h^{0.2})}} \tag{5.30}$$

For molding a 1-m polyethylene cube with a thickness of 6 mm, a vent tube diameter of 25.3 mm is predicted.

There are a number of important elements in this Example. First, if the mold parting line is not well sealed, some of the air will escape through it during the heating stage, before the plastic has started to adhere to the mold wall. This adhesion will start when the mold wall reaches about 100°C. After 100°C, all the air must pass through the vent. A quick calculation using the Charles' law, as shown earlier, indicates that as the mold is heated from about 120°C to 200°C, only 20% of the volume of the gas in the mold must pass through the vent tube during the heating stage. If this value of 0.2 is substituted into the above equation (instead of the value of 0.59 used in the example), then clearly a smaller vent size is predicted. However, during cooling, all the gas that was expelled from the mold must pass back in through the vent tube and so the larger vent diameter predicted by the above equation is probably more realistic. Even though the cooling in the mold is seldom taken back to the starting point of 25°C, the cooling rate is often faster. As a result, it is better to err on the large side in regard to vent dimensions.

Note that it is debatable whether or not it is necessary to allow for the bulk density of the powder when calculating the volume of gas in the mold. It could be argued that although the bulk of the powder leaves less free air space in the mold, the spaces between the particles are filled with air and so a more realistic estimate for the volume of air initially is $(D\text{-}2h)^3$. In fact it can be shown that it makes little difference to the predicted vent diameter whether the bulk density of the powder is included or ignored.

Possibly the most important point arising from the above Example is the fact that the vent diameter is very dependent on the oven time. Thus, thick molded parts require a smaller vent size than thin parts because they have a longer cycle time and there is more opportunity for the air to escape. This is illustrated in Figure 5.30, which is plotted from the data in the above Example.

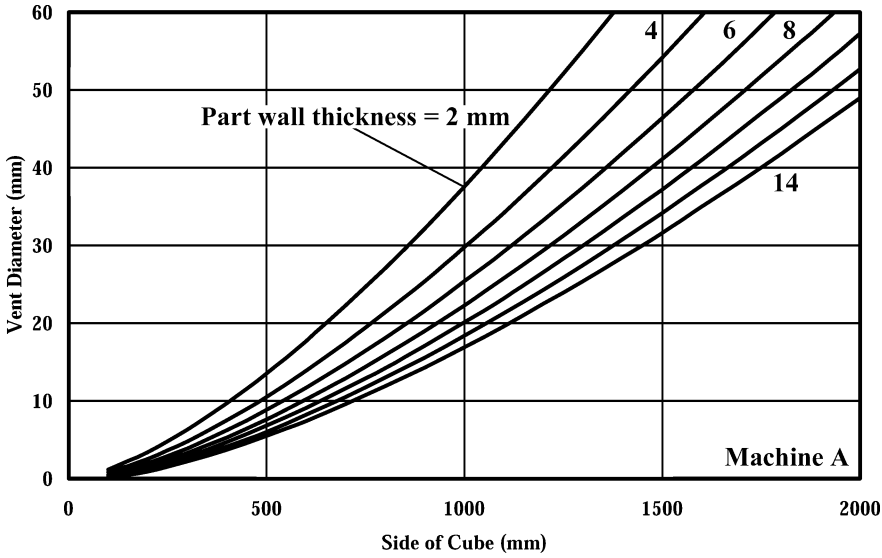


Figure 5.30 Vent size as a function of mold size and part wall thickness, used with permission of The Queen's University, Belfast

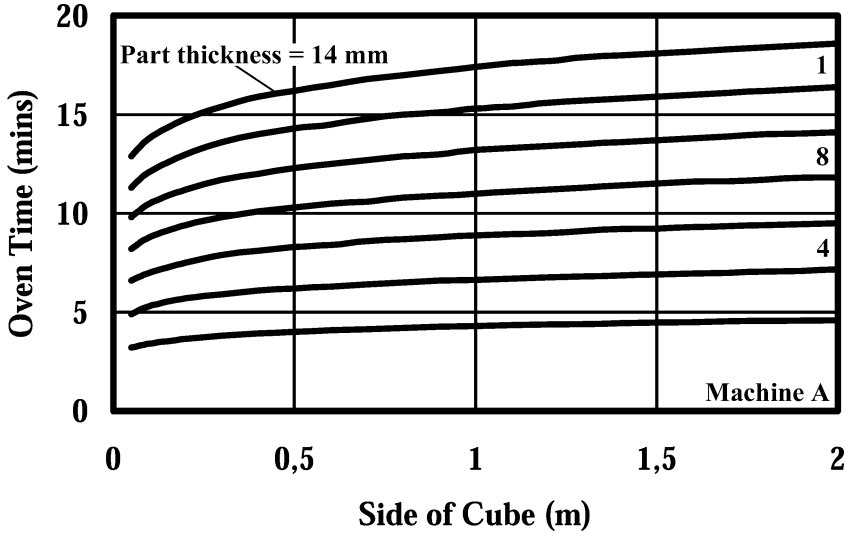


Figure 5.31 Oven time as a function of size of mold and part wall thickness — Machine A, used with permission of The Queen's University, Belfast

It can be seen that whereas a 25-mm diameter vent tube is recommended for a 6-mm thick part, a 20-mm diameter tube will do the same job for a 10-mm thick part. The mold volume is assumed to be the same in each case. In a similar way, the efficiency of the heating has a marked effect on the size of the vent tube that is needed. The above analysis has been done for a particular rotational molding machine (Machine A) where data had been collected for oven time as a function of mold size and part thickness. The characteristic for the machine is plotted in Figure 5.31. Similar tests on another machine (Machine B) are given in a different format in Figure 5.32. It can be seen that Machine B is less efficient in that for an oven temperature of 350°C, the oven time for a 6-mm thick part is about twice that recorded on Machine A. If the above analysis is modified for the longer cycle times on Machine B, then Figure 5.33 is obtained. This shows that smaller vent diameters are predicted for all mold sizes and part thicknesses. For the 6-mm part referred to in the Example, the predicted vent diameter is 17.9 mm for Machine B.

As a final point on this analysis, if the gas velocity through the vent in Machine B is taken as 1 m/s instead of 2 m/s (and a smaller value is probably more realistic), then the vent diameters will increase to the values calculated for Machine A. In fact it is likely that the gas velocity through the vent is very low because the driving force is the pressure gradient. In the above analysis, it has been assumed that there is a constant pressure gradient (equal to the maximum value achieved during the cycle) forcing the air out through the vent. If the vent is working correctly then the pressure build-up in the mold will always be negligible. Every time the pressure tries to increase, some air will leave the mold and the pressure will drop back to atmospheric. During rotational molding there is plenty of time for this to happen, so it is likely that in a properly operating system there is a steady, but small, flow of air in and out of the vent throughout the cycle. The use of wire wool or similar material, placed in the vent to stop powder from leaving, will obstruct the free flow of air and so it is likely that this causes a modest pressure build-up during heating and a modest partial vacuum or pressure below atmospheric during cooling.

The above analysis illustrates the imprecise nature of venting in rotational molding. The challenge facing the molder regarding the need for different sizes of vents for different molds on the same arm, or a different vent when a particular mold is put on a different machine, is in direct conflict with the crucial importance of proper venting.[6]

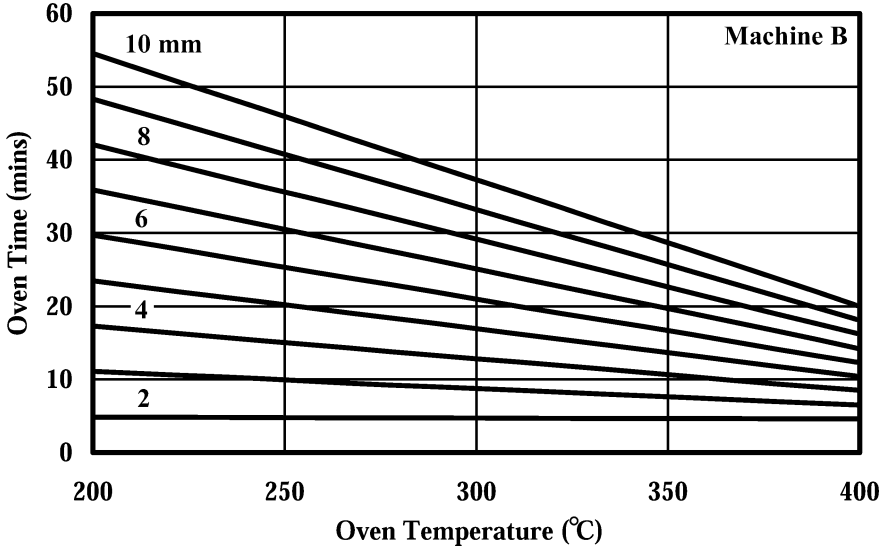


Figure 5.32 Oven time as a function of oven temperature and part wall thickness — Machine B, used with permission of The Queen's University, Belfast

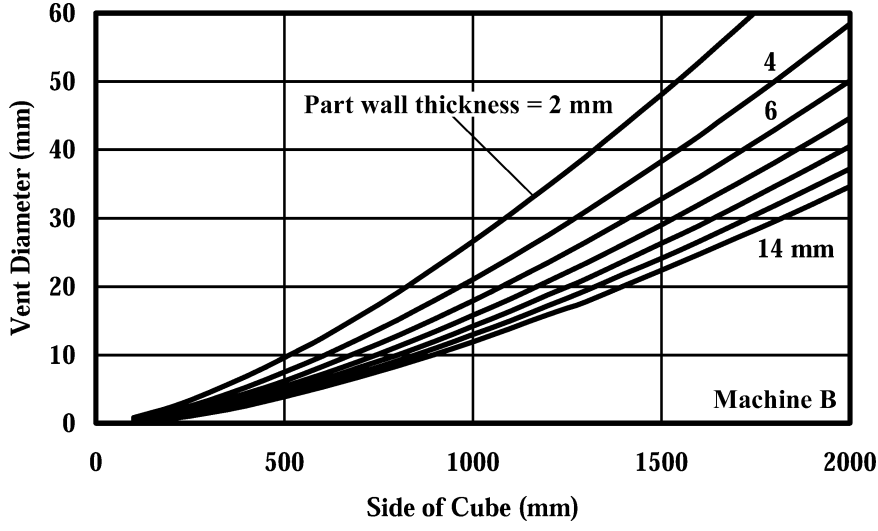


Figure 5.33 Vent size as a function of mold size and part wall thickness — Machine B, used with permission of The Queen's University, Belfast

5.5.2 *Types of Vent*

As indicated in the previous sections, the purpose of the vent is to allow equalization of pressure inside and outside the mold throughout the cycle. The prime requirements of the vent are that it:

1. Offers ease of airflow at essentially no pressure drop
2. Prevents powder from escaping from the mold cavity
3. Is able to withstand the oven air temperature and thermal cycling
4. Is easily cleaned or, if disposable, must be inexpensive
5. Is placed in noncritical regions on the mold surface, such as areas that are to be trimmed or removed after molding, or in regions where the hole(s) can be plugged
6. Reaches deeply into the mold cavity, to minimize contact with the powder and the heated mold

Commonly, the vent pipe is packed with glass or wire wool, to minimize powder flow down the pipe and out into the oven. Two types of vent pipes are used.

1. The disposable vent pipe is most common. It is PTFE tubing containing glass wool that is pressed through a special flexible bushing at the mold wall (Figure 5.34). After each molding, the tubing is manually removed and the glass wool is pushed from the tubing. The glass wool is vacuum-cleaned of powder, inspected for residual sintermelt, dried of the water adsorbed during the cooling portion of the cycle, and either reinserted or discarded in favor of a clean piece. The tubing is inspected for deterioration and is either reused or discarded in favor of a new piece.
2. Nondisposable or semipermanent vents are used when an extensive production run is planned (Figure 5.35). Although these vents are affixed through the mold walls in permanent fashion, they should be relatively easily removable for inspection and cleaning. All vent pipes should be shaped in such a fashion as to minimize water infiltration to the mold cavity. Water traces on the inside of a molded part are indicators of the most common indication of vent pipe failure.

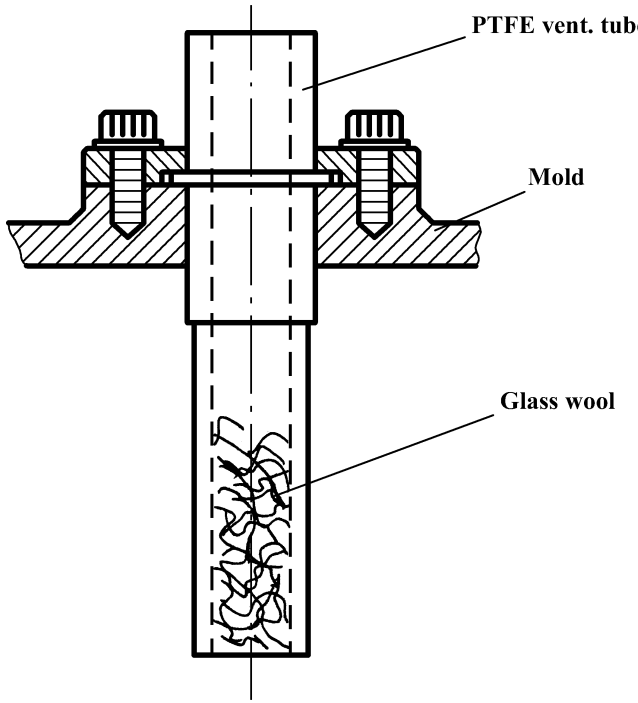


Figure 5.34 PTFE vent tube, courtesy of Wheeler-Boyce, USA

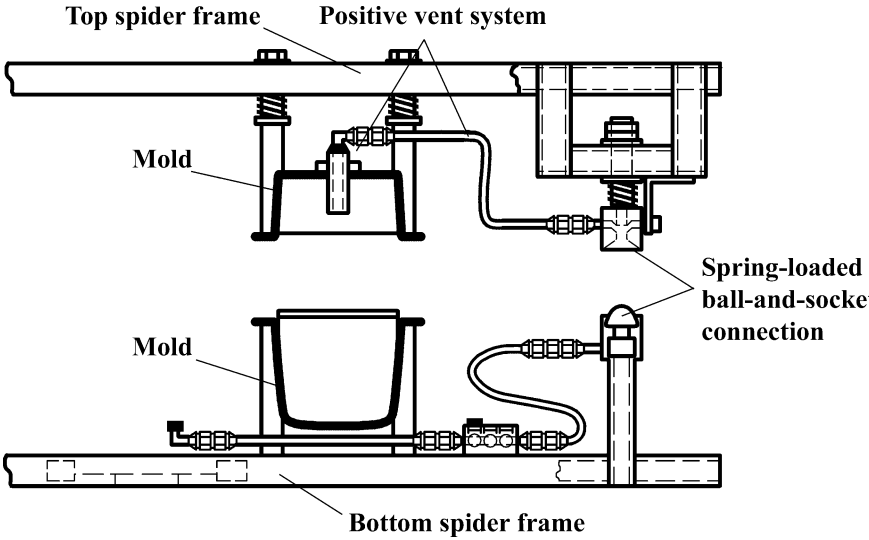


Figure 5.35 Gas transfer assembly including venting, courtesy of Wheeler-Boyce, USA

5.5.3 *Is a Vent Necessary?*

Vents are a long established part of the rotational molding process but are they really needed? It has been pointed out in the above discussion that their purpose is to ensure that the pressure in the mold remains at, or close to, atmospheric pressure throughout the cycle. But why can the pressure inside the mold not be allowed to increase to 1.6 times atmospheric pressure? After all, in injection molding the pressure in the mold can be about 1000 times atmospheric pressure.

The reason why the pressure in a rotational mold should be kept close to atmospheric is simply because the parting line is poorly sealed and the molds are thin walled. The forces generated due to pressure or vacuum could distort the mold. If these two issues are addressed, could the vent be removed completely? If the mold was perfectly sealed then any pressure generated inside the mold during heating will not cause problems such as blowholes, because the plastic melt will not experience a pressure differential with the pressure inside the mold higher than atmospheric pressure outside. All that will happen is that the plastic will be forced against the mold. And as shown elsewhere, this positive pressure on the melt during sintering/consolidation is a good thing. During cooling the pressure inside the mold will keep the plastic against the mold wall and this is also highly desirable. Hence, if the mold could be perfectly sealed, the pressure generated in the mold due to the absence of the vent is likely to be beneficial.

The question of mold distortion due to the pressure inside the mold is likely to be a bigger issue. The force generated inside the mold is the product of the pressure and the projected area on which it acts. In a cylindrical mold 2 m in diameter and 3 m long, the projected area is 6 m^2 and the opening force on the mold is typically about 360 kN (81,000 lb_f). This is a very significant force and substantial clamping arrangements would be needed to resist this force and prevent the mold from opening. With such large forces it is also understandable that there are concerns about distortion or damage to the shell-like mold. Nevertheless, for smaller types of mold where the internal forces become more manageable, it may well be worth thinking about improving the quality of the parting line and the clamping arrangement in order to reap the potential benefits of not requiring a vent. Also, even in large molds it may be possible to apply some engineering ingenuity to cope with the large forces. For example, a relatively small pressure on the inside causes a high force because it is acting on a large area, but the opposite is also true in that a small pressure acting on the outside of the mold could counterbalance the internal

force. Or a partial vacuum could be applied inside the mold to lessen the effect of the internal pressure. These are the types of things that need to be considered in machines of the future.

5.6 Mold Surface Finish

Over-specification of surface finish is a common problem in rotational molding. Since rotational molding is a zero-pressure powder process, highly polished molds are usually not desired. Rotating powder will not temporarily adhere to a highly polished mold. As a result, the powder pool or bed does not tumble but instead slides along the bottom of the mold. As noted in the Process section, this leads to nonuniform temperature through the powder bed. And the molten polymer cannot adequately replicate the surface of a highly polished mold. Typically, molds are finished by sand or grit blasting, using 100- to 200-mesh particles. In this way, a matte finish is applied to the mold surface. Chemical etching is used when a specific surface texture such as leather is required. Porosity can occur during etching with cast aluminum molds and welded areas on steel and stainless steel molds usually do not etch to the same level as surrounding areas. Uniform surface finishes are difficult in deep recesses. All draft angles must be increased as the depth of texture increases. One rule of thumb is that all draft angles should be increased one degree for each 0.010 inch (0.25 mm) of texture depth. It must be noted that all surface finishes are highly labor intensive and therefore, can be very costly. In addition, the initial surface texture can be substantially altered if permanent mold releases are added to the mold surface.

5.7 Mold Releases

Rotational molding is a near-zero pressure process, where for the most part the liquid polymer is coating the inside of the mold surface. When the polymer cools and solidifies, it shrinks away from the mold surface. Relatively simple designs can have zero or even negative draft angles and the parts will release cleanly from the mold. For designs containing internal ribs, stand-up bosses, kiss-offs, near-kiss-offs, or deep double walls, the cooling polymer will shrink onto any male portion of the mold surface. As a result, adequate draft angles must be provided, with additional allowances made for texture on the surface. Part design characteristics are discussed elsewhere. There are instances where certain polymers can stick in even simple six-sided box designs. As a result, mold releases are

used. The object of the mold release is to interfere somehow with the adhesion of the polymer with the mold surface. It has been estimated that there are more than 250 types of mold releases, ranging from releases for the one-time application to permanent mold releases on both the inside and outside of the mold. Some of these are discussed below.

5.7.1 *Spray-on Zinc Stearates*

These are usually in powdered aerosol form, and can be sprayed on the mold in particularly difficult areas. However, manual application never yields a controlled film and ultimately the build-up becomes messy, plate-out occurs, and the molds must then be thoroughly cleaned. Nevertheless, stearates are relatively cheap.

5.7.2 *Silicones*

These are true slip agents, being chemically inert. They simply form a mechanical interference between the polymer and the mold. These cannot be used for aerospace applications and certain FDA applications. Some advanced silicones crosslink and temporarily bond to the mold. Usually, silicones are temporary mold releases, meaning that they must be replaced every few cycles.

5.7.3 *Disiloxanes*

These are semipermanent mold releases. Disiloxanes chemically bond to the mold surface to form a layer that is about 4 microns thick. They are thermally stable to 800–900°F or 425–480°C. Typically, 1 to 1000 parts can be pulled from a disiloxane-coated mold before it needs to be re-coated.

5.7.4 *Fluoropolymers*

These are permanent mold releases or mold coatings. Although they are referred to as "Teflons," they are really fully halogenated ethylene polymers, rather than tetrafluoroethylene polymers. The latter are too soft and chemically inert to be useful as mold coatings. These fluoropolymers are an industrial version of the frying pan coating and are usually recommended for temperatures less than about 600°F or 315°C. This limits their use with engineering polymers. Unlike the disiloxanes, fluoropolymers do not fill in voids. Typically, 10,000 or more parts can be pulled from a fluoro-

polymer-coated mold before it needs recoating. More typically, however, the mold needs to be recoated before this time because of accidental scraping or scratching of the surface during part removal. It is recommended that only UHMWPE tools be used against a fluoropolymer coating. Owing to the difficult and patented procedure for applying these coatings, they cannot be applied in-house. And for the same reason, these coatings cannot be field-repaired.

The key to successful semipermanent and permanent mold release coating is in mold surface preparation. The recommended procedure is to wash the mold surface first with soap and water, followed with a hydrocarbon solvent wipe, such as acetone. The surface should then be sand or grit blasted. Several coatings of mold release are required, each as thin and uniform as possible. The number of coatings depends on the thermal stability of the polymer composition, the mold geometry, the part geometry, the mold surface porosity, and the surface quality and texture. The release agent must be suited to the mold material, the process environment, changes in production, polymer-to-release agent reaction, and the amount of shear between the part and the mold during demolding. LDPE and HDPE release well from disiloxanes and fluoropolymers. LLDPE is more difficult to release from disiloxane than from fluoropolymer. XLPE is very difficult to release from disiloxane and somewhat less difficult from fluoropolymer. Polycarbonate and nylon are really tenacious with disiloxane. A higher temperature fluoropolymer is now available that yields a matte finish with these polymers but allows them to release satisfactorily.

5.7.5 *Mold Surfaces to be Coated*

It is apparent that the interior of the mold is the primary region for coating. But the parting lines are as important, since a build-up of degraded polymer in the corners of tongue-and-groove and lap-joint parting lines serves to hold the mold open locally, inviting blowholes and further powder build-up. For certain polymers, such as plastisols and other liquids such as nylon 6, acrylic syrup, and epoxies, the outsides of the molds and spiders catch servicing drips and slops and leaks from improperly sealed molds. These materials bake on to produce shellac that can interfere with mold actions. For PVC materials, the degraded polymer produces hydrogen chloride gas that is corrosive to steel. High-temperature fluoropolymers are now available for coating the outsides of these molds, as well as spider surfaces, thus minimizing shellac build-up.

Again, these coatings are not inexpensive, and can save substantial downtime for cleaning and corrosion repair.

5.7.6 *Controlled Release*

Problems with *warpage* can sometimes be traced to improper mold release agents. If the part is prematurely or unevenly released from the mold during cooling, it will cool improperly and unevenly and may warp. If the part releases near the end of the cooling cycle, it may not shrink enough to be released from the mold, despite adequate draft angles. If the mold release is considered to be suitable for the mold and the polymer, the amount of release agent used may not be correct. Excessive mold release will cause early separation of the part from the mold wall, whereas insufficient mold release may release the part later in the process cycle. The biggest problem is inconsistent release because this will result in a variation in warpage and shrinkage from part to part. This is discussed in detail later.

5.7.7 *Mold Release Cost*

The total cost of releasing the part from the mold includes release agent costs, direct labor to apply the agents, indirect labor, overhead, and the cost of mold preparation. Most of the cost of a release agent is in mold preparation, not in release agent costs. There are hidden benefits as well, since the parts typically require little brute strength to force them free of the mold surfaces. In properly prepared molds, parts can be simply dropped from the mold cavities.

References

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6 PROCESSING

6.0 Introduction to Heating

Rotational molding begins with powder and then focuses on powder flow, sinter-melting or coalescence, densification, and cooling of the polymer. Each of these processing aspects is considered in detail in this chapter. Since cycle time prediction, in general, and those aspects of the process that dominate the cycle time, in particular, are important, mathematical models are proposed for each aspect of the process.

6.1 General Anatomy of the Rotational Molding Cycle

Recent technical developments have allowed continuous temperatures to be taken at various locations in and around the mold.[1] Figure 6.1 shows these temperatures for the entire heating and cooling cycle for a mold rotating in a near-isothermal hot air oven environment. As noted below, the outside mold surface temperature exhibits a classic first-order transient response to a step change in the environmental temperature. For most mold materials, there should be relatively little difference between the outside mold surface temperature and the inside mold surface temperature. As shown in Figure 6.1, the temperature difference across the mold is measured at about 10°C to 30°C, a value much larger than expected. However, temperature differences of this magnitude have been measured on static molds held in hot air ovens.[2,3] While heat loss to the ambient mold cavity air and the cold polymer powder may account for a portion of this temperature difference, the source of the majority of the difference remains unexplained.*

Note also that while the outside mold temperature increases rapidly from the moment the mold assembly enters the oven, the internal mold cavity air temperature exhibits a substantial lag. Certainly the rotating powder absorbs substantial energy, thus retarding energy transfer to the mold cavity air. The mold cavity air temperature curve, shown in detail in

* One explanation is that the thermocouple recording the outer surface temperature of the mold may be picking up heat from the oven and so is recording a higher value than the actual mold temperature. However, in at least one instance,[3] the thermocouple tip was peened into the mold surface.

Figure 6.2, frequently shows a point of departure from the tangent, point A. The temperature obtained by extending a vertical line to the inside mold surface temperature curve is probably a measure of the *powder tack temperature*, or the temperature where powder first sticks to the mold surface.

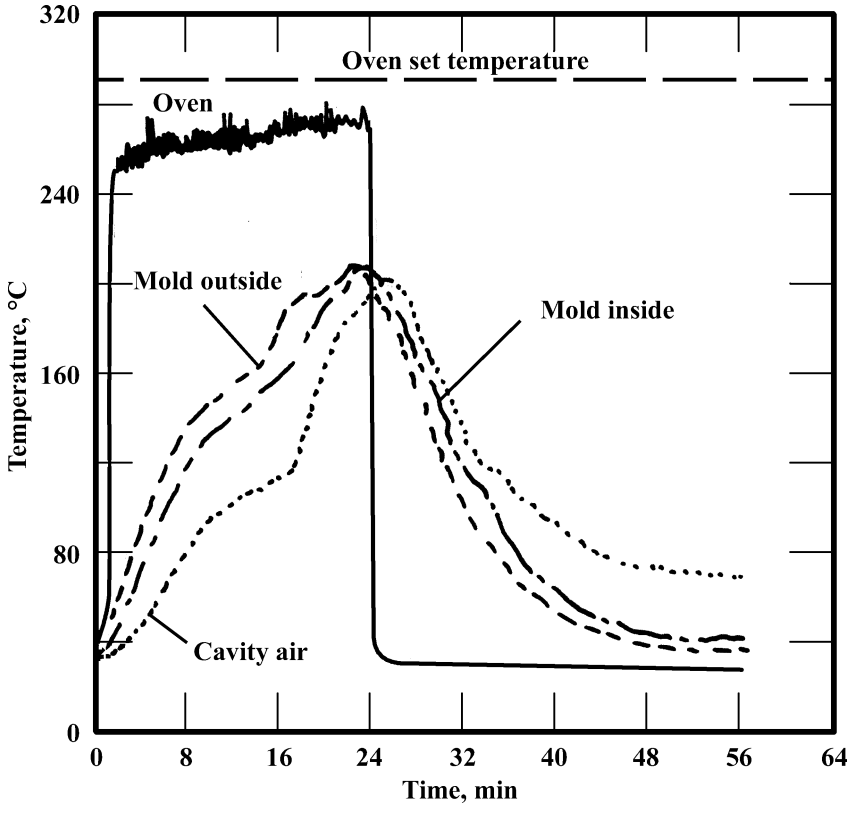

Figure 6.1 Typical thermal traces of various regions obtained using the Rotolog™ temperature measuring system, used with permission of The Queen's University, Belfast

The kink in the mold cavity air temperature at point B yields additional heuristic information. First, the shape of this curve to this point is a direct result of powder adhering to the mold surface. Since the powder layer grows thicker as the powder bed is consumed, the resistance to energy transmission increases. As a result, the temperature difference between the outside mold surface and the mold cavity air increases. The

decrease in the rate of rise of the internal air temperature is also the result of plastic melting and absorbing most of the heat input from the oven. Since the mold cavity air temperature mimics the inside surface temperature of the polymer bed, a transition (point B) indicates approximately the time when the last of the polymer has adhered to the mold wall and coalescence and densification are proceeding.

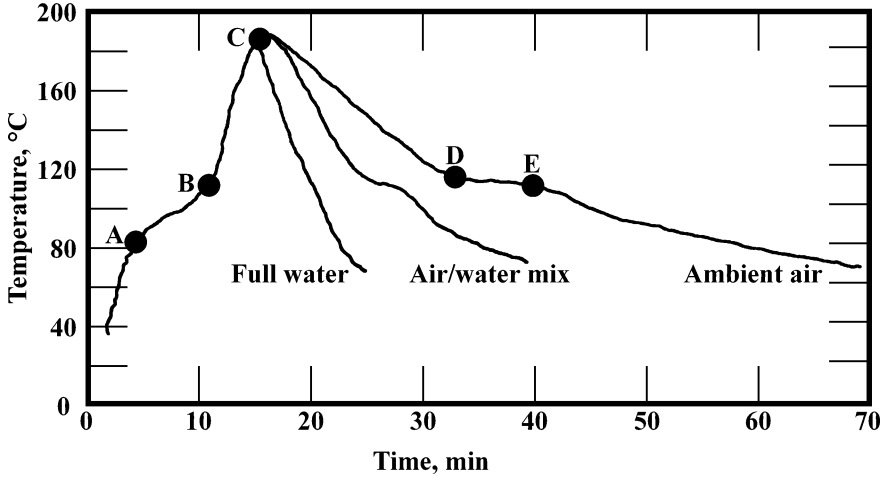

Figure 6.2 Actual mold cavity air temperature traces, showing effect of cooling medium on cooling time, courtesy of Queen's University, Belfast.

During coalescence and densification, air is eliminated from the polymer, and the polymer layer decreases in thickness. As a result, the resistance to energy transmission decreases and the temperature difference between the outside mold surface and the mold cavity air decreases. This is seen as a decrease in the difference between the outside mold surface temperature and the mold cavity air temperature. Also, as the polymer is nearly completely melted, there is a closer correlation between mold and air temperature profiles. This is apparent by comparing Figures 6.1 and 6.2, between points B and C.

Once coalescence and densification are complete and the polymer layer is monolithic, the mold can be removed from the oven. This event is seen in Figure 6.2 by the abrupt drop in outside mold surface temperature. As is expected, the mold surface temperature decreases as a first-order response to a change in the external temperature. The inner mold surface

temperature, exhibiting a thermal resistance, lags behind the outside mold surface temperature. As expected, the mold cavity air temperature responds even more slowly to the change in environmental temperature. The roundness of the mold cavity air temperature curve at its apex, point C, is because of thermal inversion in the polymer melt layer. That is, when the mold first exits the oven, the polymer against the mold surface is hotter than that in contact with the mold cavity air. As the mold cools, the temperature of the polymer against the mold surface rapidly drops below that in contact with the mold cavity air. The thermal inversion process through the polymer thickness takes time. The measured result is a rounding of the apex of the mold cavity air temperature. The extent of the overshoot of cavity internal air temperature depends on the wall thickness of the part, as detailed later in this chapter.

The polymer now cools for some time at a rate approximately that of the mold itself, with the mold cavity air temperature lagging behind the mold surface air temperature because of the thermal resistance of the molten polymer layer. Another kink, for crystalline polymers such as polyethylene and polypropylene, is observed at point D, where crystallization is occurring. Since crystallization is an exothermic process, giving off heat, the effect is seen as an inflection or flattening of the mold cavity air temperature. This condition continues until the polymer crystallization ceases, point E. Frequently, another, rather poorly-defined inflection, point F, in the mold cavity air temperature trace is seen. This inflection is attributed to the point where the plastic part shrinks away from the inner mold surface.

As discussed in Chapter 4, internal air temperature measurement is a powerful tool for determining parametric changes in polymer materials, dosage levels, mold material characteristics, oven temperatures, and cooling sequences.

6.2 General Process Description

Before considering the rotational molding cycle in detail, consider the following summary of the process. The heating cycle begins with powder charging at the service station and ends when the mold assembly is removed from the oven to the cooling station. The cooling portion of the cycle begins with the mold exiting the oven and ends with part removal. Table 6.1 details the various phenomenological steps to be considered in detail in this chapter.

Table 6.1 Steps in the Rotational Molding Cycle

Step	Comments/Concerns
Powder charging	Bulk density of the powder, place for powder in narrow molds
Initial heating	Characteristics of powder bed
Tacking condition	Hot tack temperature of powder
Particle coalescence	Three-dimensional structure
Densification	Capillary flow, powder structure collapse, air inclusion
Egress from oven	Thermal inversion in polymer melt layer
Initial cooling	Characteristics of cooling melt
Recrystallization	Recrystallization temperature, rate of crystallization, rate of cooling
Final cooling	Shrinkage during and after crystallization, separation from mold surface

6.3 Powder Behavior

Rotational molding grade powder has both solid and fluid-like characteristics. In Chapters 2, 3, and 5, solid mechanical characteristics such as particle size distribution, shape characteristics, and packing density were discussed, particularly as influenced by grinding or pulverizing techniques and methods. During the early oven rotation time in the closed mold, the powder behaves in a fluid-like manner. That is, as the mold rotates, powder particles tumble or "flow" over one another. Typical flow is best demonstrated by adding powder to a horizontally rotating cylinder.[4–6] * As discussed earlier, rotational molding grade polymer powder has a particle size range of -35 mesh to + 200 mesh. The powder is usually manually charged to the mold while the mold is in the open configuration in the servicing stage of the process cycle. The typical poured but untamped powder packing fraction range is 0.35 to 0.50, but this can vary widely, depending on polymer type and grinding characteristics.[7] The bulk density range for typical rotational molding polymers, as poured, is given in Table 6.2.

* The use of the horizontal cylinder to evaluate bulk powder flow is discussed below.

Table 6.2 Typical Powder Bulk Density

Polymer	Compact Density (kg/m^3)	Reduced Density	Bulk Density (kg/m^3)	Bulk Density (lb/ft^3)
LLDPE	910	0.38 – 0.43	345 to 390	22 to 24
HDPE	960	0.35 – 0.50	335 to 480	23 to 30
PS	1050	0.30 – 0.55	315 to 580	22 to 36
PP	910	0.25 – 0.40	230 to 365	14 to 23
Nylon	1100	0.40 – 0.60	440 to 660	27 to 41
FEP	2200	0.25 – 0.40	550 to 880	34 to 55

Several aspects of powder charging are important. First, there must be room for the powder in one mold section during charging. For asymmetric molds, the deeper portion should be filled. The powder must be freely poured, and must not be tamped. Then, there needs to be free space for the tumbling powder during the early portion of the heating cycle. Nonuniform wall thickness and severe corner bridging result when the powder cannot freely flow across the mold surface. And powder must be carefully distributed when the mold has both large and small cross-sections. A classic example is a hobby horse, where the leg cross-sections are substantially less than that of the body.

Determination of the required amount of powder in a specific charge is quite straightforward. The inner mold surface area is determined, either manually or from CAE software. Tool path software yields one of the most accurate surface area values. The anticipated uniform wall thickness is obtained either from prior experience or from finite element analysis. The product of the area and the wall thickness yields the volume of plastic required in the finished part. The weight of polymer is determined by multiplying the volume by the polymer density, as illustrated in Chapter 5.

Fluidizing powder must have room to freely move throughout the mold interior. For a specific example, it is recommended that the absolute minimum distance between parallel walls be three times the nominal wall thickness of the fused polymer.[8] The recommended minimum distance is five times the nominal wall thickness. These recommendations translate into a maximum reduced bulk density of charged powder of 0.67 for the absolute minimum spacing and 0.40 for the recommended minimum spacing.

In certain instances, these minimum spacings may not be sufficient to prevent *bridging*, or the formation of polymer connections between the parallel walls.

Airborne dust is a major problem with manual powder charging into an open mold half. Dust can be minimized by filling through an access way in an already-closed mold, or by using a drop box mounted to the access way. It can also be minimized by using micropellets or powders that have been compacted into pills or tablets. And research underway indicates that it may be possible to feed powder continuously, directly into the mold cavity, through the machine arm.[9]

6.4 Characteristics of Powder Flow

Rotational molding speeds are quite low, typically about 4 to 20 rev/min or so. As a result, the powder charge remains as a powder bed near the bottom of the mold throughout the early portion of the heating cycle. Polymer powders can be classified as either *Coulomb flow powders* or *viscous flow powders*.[10] For Coulomb flow powders, the particles remain in continuous contact with their neighbors in any situation. For viscous flow powder, contact forces are resisted by momentum transfer between particles that move relative to one another. These two classifications are seen in rotational molding. Three types of bed motion have been observed* (Figure 6.3).[12]

Steady-state Circulation. For steady-state circulation of the powder in the bed, the powder at the mold surface moves with the mold surface until the mass exceeds the dynamic angle of repose. For most polymer powders, this angle is between 25° and 50° above the horizontal. At that point, the mass breaks away from the mold wall, and cascades across the static surface of the bulk of the powder bed. This type of flow is continuous and the flow rate is altered only by the geometry of the mold itself. Powder having this type of flow behavior is usually characterized as spherical or squared-egg in shape and as freely flowing. Powders that exhibit steady-state circulation are classified as viscous flow powders. Steady-state circulation is observed when the mold surface is quite rough, the particle sizes are quite large, and powder volume is moderate when compared with the mold volume.

* The terms steady-state circulation, avalanche flow, and slip flow were proposed by M.-S. Sohn.[11]

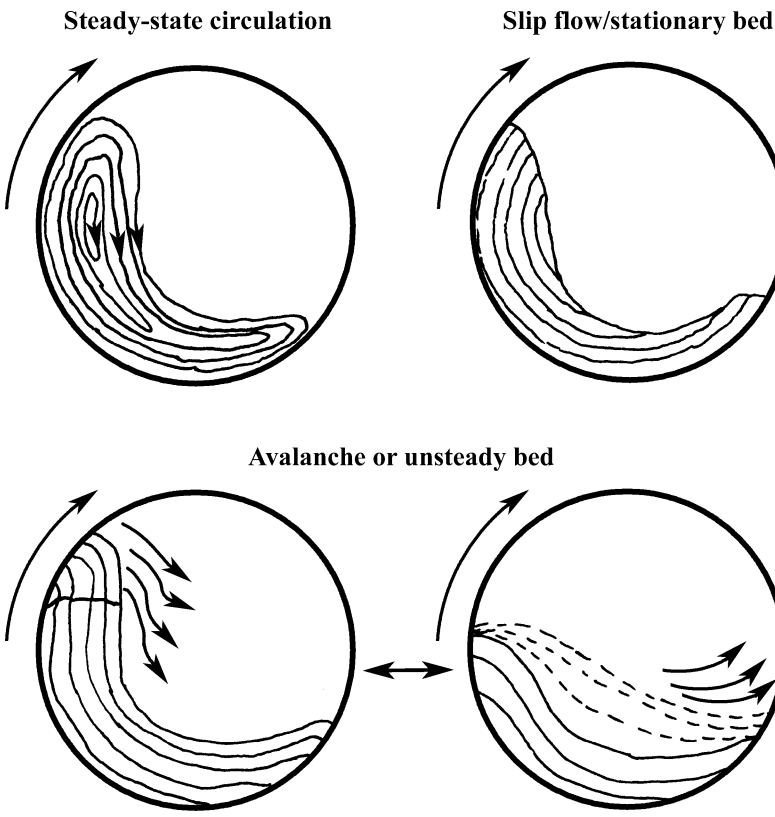

Figure 6.3 Three types of powder bed circulation[12]

Avalanche Flow. This mode of circulation is analogous to snow avalanche. Initially, the powder in the bed is static with respect to the mold surface. The mold raises the powder bed until the entire mass exceeds the dynamic angle of repose. At that point, the top portion of the mass breaks away from the mold wall, and cascades across the rest of the powder bed. The bed then becomes static and is again raised by the rotating mold. It is known that avalanche flow occurs when the powder is slightly tacky or is not free-flowing, and when the powder is acicular or two-dimensional. Since avalanche flow is not a steady-state flow, it cannot be classified as either viscous flow or Coulomb flow. Avalanche flow is sometimes observed as the powder bed is depleted during the heating phase of the process.

Slip Flow. This type of flow occurs when the mold surface is very smooth. There are two types of slip flow. The more common slip flow is really a

cyclical slip-stick flow. Initially, the powder in the bed is static with respect to the mold surface, as with the avalanche flow. As the mold raises the powder bed, the entire mass reaches a point where the friction between the powder and the mold wall is no longer sufficient to prevent the mass from sliding against the mold surface. At that point, the entire static bed simply slides to the bottom of the mold, without any measurable type of powder circulation. The bed then stops sliding and is again raised by the rotating mold.

Table 6.3 Types of Powder Flow — Rotational Molding

Type	Comment
Steady-state circulation	Ideal flow
	Maximum mixing
	Best heat transfer
	Spherical or squared egg particle shape
	Cohesive-free or freely flowing powders
	Smooth powder surfaces
	Relatively high friction between mold surface and powder bed
Avalanche	Adequate powder flow
	Relatively good powder mixing
	Relatively good heat transfer
	Squared egg, acicular, or disk-like particles
	High friction between mold surface and powder bed
Slip flow	Poor powder flow
	No powder mixing
	Poor heat transfer
	Disk-like, acicular particles
	Powders with high adhesion or cohesion
	Agglomerating or sticky powders
	Very low friction between mold surface and powder bed

The less common slip flow is a steady state slip. For this type of slip, the bed essentially remains fixed relative to the horizontal axis of the mold and the mold simply slides beneath it. Powders that pack well and that have very low coefficients of friction with the mold material, such as olefins and FEP, will exhibit slip flow, particularly if the mold is also plated or highly polished. Early permanent Teflon™ mold releases also promoted slip flow. Powders that exhibit slip flow are classified as Coulomb flow powders. Slip flow is also observed when the mold surface is very smooth, or the powder volume is large compared with the mold cavity volume.

Table 6.3 summarizes these major types of powder flow.

Usually, portions of the polymer powder particles fluidize during avalanche and steady-state bed flows. From in-mold cameras and from diminution of light through rotating beds, particle size segregation and decreases in overall powder bulk density are observed, particularly in the layers farthest from the mold surface.

6.5 Rheology of Powder Flow

There is substantial debate as to the best way to treat the mechanics of powder flow. In reality, flowing powders are discrete particles that are temporarily suspended in air, thus presenting a dynamic two-phase system. Single powder particles falling in quiescent air or another fluid are characterized by Stokes flow. That is, the drag force on the particle is directly proportional to its relative velocity, with gravity being the only body force. Fluidization is the lifting of a stationary bed of particles by upward flow of air or another fluid. As the particle density increases, Stokes flow is compromised by interparticle collisions, where kinetic energy interchange occurs. Throughout most of the rotational molding process, there are so many particles interacting with one another, in swarms or as streams, that most discrete particle theories cannot be used. The possible exception is during the latter stages of powder flow, when most of the polymer is adhered to the mold surface or to other pieces of powder.

There have been many studies on the rheological or flow characteristics of powders.[13–20] Because the rheological problem deals with multiphase flow, or moving particles in moving air, in which one of the phases, air, has essentially no viscosity or density, granular flow has yet to be fully understood.

Two approaches are generally considered. The first assumes that the multiphase flow is a continuum. That is, the particles affect the multiphase bulk properties such as density and viscosity but particle-to-particle interaction is ignored or considered insignificant. The concept of viscosity of a flowing powder stream, proposed many years ago, has not received wide acceptance.[14] This concept is based on the decrease in velocity of a falling powder layer owing to shear with a solid inclined plane. This decrease implies a shear layer or region and a resistance to flow. Additional work indicates that the velocity of a flowing powder stream is not necessarily maximum at the free surface, and that a viscosity of sorts is defined only when the shear surface is static. When the shear surface exchanges particles with the flowing surface, the flowing fluid can either increase or decrease in mass during flow across the shear surface. The change in mass is dependent on the effect of external factors such as gravity, fluid velocity, the relative size and shape of the particles, and the relative boundary conditions.[11]

Since the multiphase bulk density changes with flow velocity and certain particle characteristics such as particle size, size distribution, and shape, traditional Newtonian viscosity* is frequently altered to include Bingham-type behavior,** dilatancy,[22, 23] or compressible flow behavior.[18] Recently, multidimensional analyses of particles with finite interaction times during collision and ancillary computer algorithms allow prediction of flow characteristics of granular swarms of like spheres.[19] These models predict that as the volume fraction of solids increases, the normal stress and the shear stress increase. Effective viscosity increases with increasing shear rate as well, supporting the contention that the powder-air multiphase is dilatant. In addition, it appears that the multiphase behavior is quite stable below a given shear rate, but quite unstable above. The transition is referred to as a "shear band." Even though this approach requires extreme simplification in particle size, shape, and size distribution, the general predictions are most promising.

Since the nature of powder bed motion is so critical to the early fusion state of the powder against the mold surface, a simple lab-scale-rotating unit should be employed to evaluate the flow behavior of new polymers and new grinding techniques. The unit shown in Figure 6.4 yields rotation in a radial direction only, as seen in Figure 6.5.[6] Nevertheless, the unit is useful for determining the effect of mold fill level on bed motion and the nature of the

* Kurikara[14] assumed Newtonian viscosity.

** Bingham fluids require a finite applied stress before they can be sheared.[21]

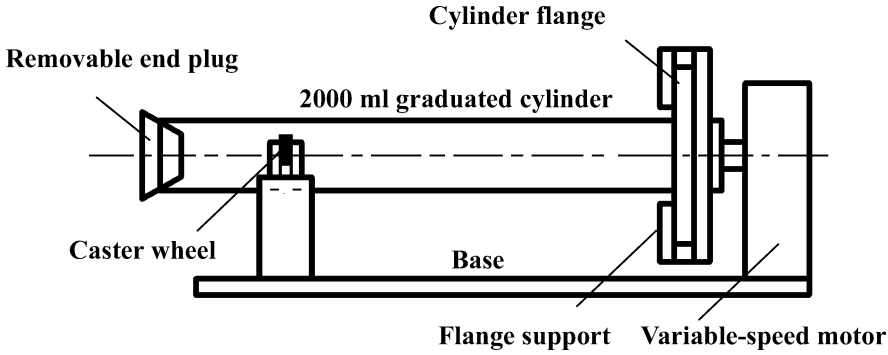

Figure 6.4 Axial powder flow apparatus

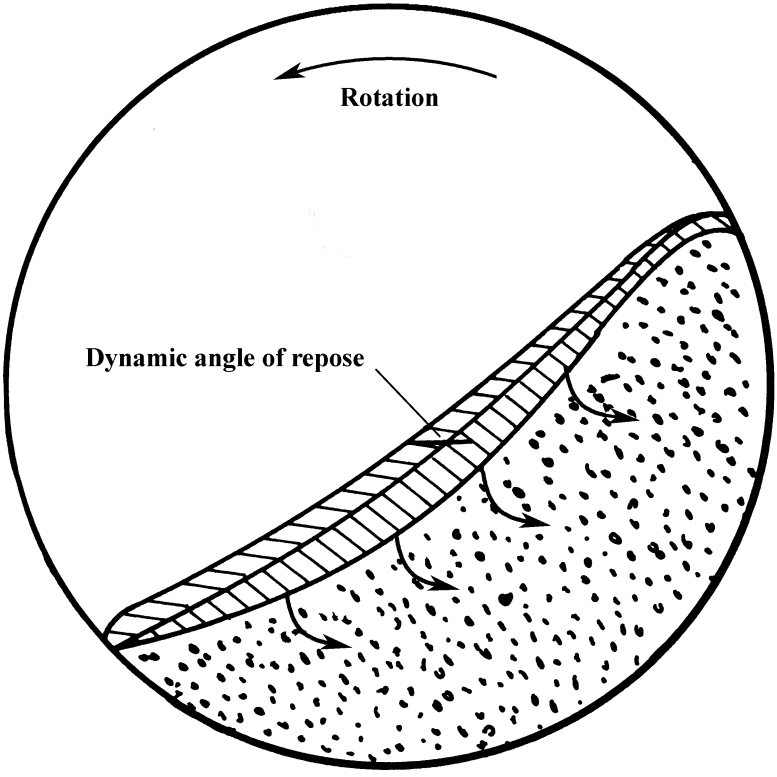

Figure 6.5 Axial powder bed motion observed in laboratory equipment[6]

powder flow characteristics during dry flow and melting. Note that the bed flow mechanism can change during heating. For example, as powder becomes tacky or begins to stick to the mold surface, the bed flow can change from slip flow to avalanche flow, or from steady-state circulation to avalanche flow. As a result, the particle-to-particle temperature uniformity can change dramatically.

6.6 Heat Transfer Concepts Applied to Rotational Molding

Three types of heat transfer occur in rotational molding. Conduction is the transmission of energy between solids. Energy is conducted through the rotational mold wall, through the stagnant polymer powder in contact with the mold wall, and through the polymer as it densifies, cools, and crystallizes against the mold wall. Convection is energy transmission through fluid flow. The heated air in the oven convects its energy through contact with the rotating mold surface, and the air inside the mold cavity is heated and cooled by convection with the inner mold surface, the rotating powder, and the densifying and cooling polymer mass. Radiation is electromagnetic energy interchange between hot and cold surfaces. Although radiation plays a minor role in heating and cooling molds and polymers, one machinery builder uses infrared energy as a heating source. Radiation is not considered in the discussion that follows.

6.7 Heating the Mold

Rotational molds are traditionally constructed of relatively thin, high thermal conductivity metals such as aluminum and steel. Typically, the mold absorbs substantially more energy than the plastic.* As the mold is heating in a nearly constant temperature air environment, its rate of heating is essentially unaffected by the small amount of thermal heat sinks offered either by the sticking, densifying plastic or the air in the mold cavity. As a result, the mold should exhibit a typical first-order response to a step change in environmental temperature. Mathematically, this is written as a conduction equation:

$$\rho\, c_p\, t\, dT/d\theta = h\,(T_{\text{air}} - T) \tag{6.1}$$

Where ρ is the density of the mold material, c_p is its specific heat, t is the mold

* This is illustrated later in this chapter and discussed in more detail in Chapter 5.

wall thickness, T is its instant temperature, θ is time, T_{air} is the environmental temperature and h is the convection heat transfer coefficient. If the initial mold temperature is T_0, the instant mold temperature is given as:

$$(T_{air} - T)/(T_{air} - T_0) = \exp[-h\theta/\rho c_p t] = \exp[-h\alpha\theta/Kt] \quad (6.2)$$

Where $\alpha = K/\rho c_p$, the thermal diffusivity of the mold material. Thermal characteristics for various mold materials are given in Chapter 5. This model assumes that the temperature across the mold wall thickness is constant and that the heat transfer coefficient on both sides of the mold wall is the same. Technically, there is a thermal lag between the oven surface of the mold and the inner or mold cavity surface. The time at which the inside mold cavity temperature first begins to increase from $T_{mold,0}$ is given approximately by:

$$\theta_{inside} \approx 0.0156L^2/\alpha \quad (6.3)$$

For all intents, the inside mold surface sees the outside mold surface energy in less than one second. Once the inner mold surface begins to heat, its temperature T_L lags behind the outside mold surface temperature T_W by approximately:*

$$T_L \approx T_W - h(T_{air} - T_W)L/2K \quad (6.4)$$

The temperature offset is about proportional to the convection heat transfer coefficient and the thickness and thermal properties of the mold material. High oven air flow, thicker molds, and molds of low thermal conductivity act to increase the temperature difference across the mold thickness. The rate of heating of both mold surfaces become equal when the heating time is approximately:

$$\theta_{asymptote} \approx 0.45L^2/\alpha \quad (6.5)$$

The thermal offset across the mold thickness may be only a few degrees at best. The shape of the transient mold heating curve has been verified through measurements on stationary and rotating molds.[1–3] Table 4.2 lists values for convection heat transfer coefficients for various fluid media. Experimentally, the convection heat transfer coefficient for molds rotating in a hot air oven is on the order of 5 Btu/ft^2 hr °F.

* This equation is technically correct for constant heat flux to the surface. The heat flux in rotational molding slowly decreases as the mold temperature increases. For this approximate analysis, it can be considered constant.

6.8 Heating Powder

As with powder flow, there are two approaches to heat transfer to the powder bed. The bulk powder bed, acting as a continuum, must be heated, and the individual powder particle must be heated.

6.8.1 *Transient Heating of an Individual Particle*

The temperature gradient through an individual powder particle is easily studied with transient heat conduction to a spherical or cubical solid. The appropriate equation for a sphere is:[24,25]

$$\frac{\partial T}{\partial \theta} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right) \tag{6.6}$$

The initial temperature is given as:

$$T(r,\theta = 0) = T_0 \tag{6.7}$$

Even though the particle may be contacting a hot mold wall or other particles, the contact areas are usually small when compared with the total surface area of the particle. As a result, the energy input at the surface is probably best determined by convection from the surrounding air:

$$-K\frac{\partial T}{\partial r}\Big|_{r=R} = h\left(T_{\text{air}} - T\right) \tag{6.8}$$

The appropriate value for h, the heat transfer coefficient, is that of quiescent air. The solution for this equation, with appropriate boundary conditions, is given graphically as Figure 6.6.[6a] Note that the time dependency is given as the dimensionless Fourier number:

$$\text{Fo} = \alpha\theta/r_0^2 \tag{6.9}$$

where α is the thermal diffusivity, $\alpha = K/\rho c_p$, θ is time, and r_0 is the radius of the powder particle. Since r_0 is very small, the Fourier number tends to be large for even the shortest time. As a result, a more appropriate approach to energy input to a powder particle focuses on a simpler model, similar to that for transient heating of the mold:

$$\rho\, c_p\, V\, dT = hA(T_{\text{air}} - T)\, d\theta \tag{6.10}$$

where V is the volume of the particle and A is its surface area. If the air

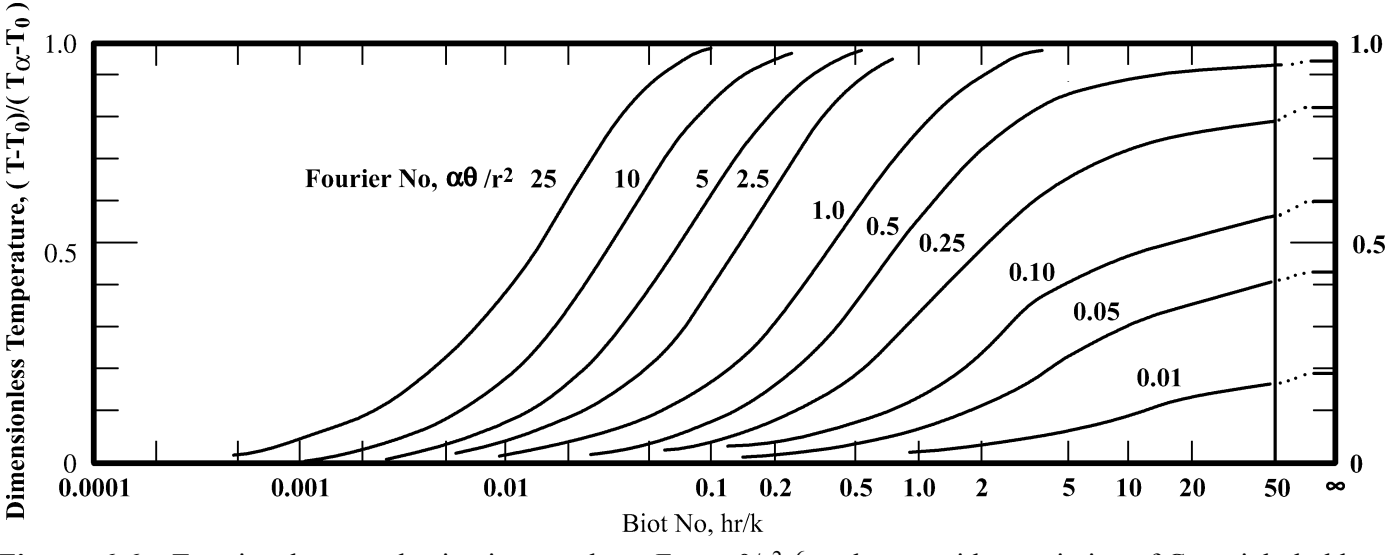

Figure 6.6 Transient heat conduction into a sphere, Fo = $\alpha\theta/r^2$, [6a] redrawn, with permission of Copyright holder

temperature is considered constant, the solution to this equation is:*

$$\frac{T_{air} - T}{T_{air} - T_0} = e^{-(h\alpha A/VK)\theta} \tag{6.11}$$

Note that this equation is similar to the transient heat transfer equation for the heating of a metal mold . The operatives here are the thermal properties of the polymer, given as α/K or $1/\rho c_p$, and the surface-to-volume ratio of the powder particle. For a perfectly smooth sphere of radius r_0, the surface-to-volume ratio is $3/r_0$. For a perfectly smooth cube of side D, the surface-to-volume ratio is $6/D$. So long as the powder is moving freely through the air in the mold cavity, however, it can be assumed that the temperature through any powder particle is essentially uniform. In other words, so long as the rotational molding powder is -35 mesh or smaller, there is no appreciable temperature gradient through a powder particle in active contact with mold cavity air.

6.8.2 *Heating the Powder Bed*

Since it is not possible at this point to adequately characterize powder flow in a rotating mold, precise modeling of energy input to flowing powder is also not possible. However, some attempts to model heating of idealized powder appear to yield reasonable results. These are discussed later in this chapter, along with heating and cooling of the consolidated polymer. The standard approach is to assume that the powder bed is behaving either in a steady-state circulation mode or steady-state static mode. For either of these models, energy is transferred into the powder bed by conduction from the mold wall. Thermal diffusivity is the operative powder bed thermal property. The effective powder bed thermal diffusivity, $\alpha_{effective}$, is given as the ratio of the thermal conductivity of the powder bed to the powder bed density and heat capacity:

$$\alpha_{effective} = K_{powder} / \rho_{powder} \times c_p \tag{6.12}$$

The thermal conductivity of the powder bed is related to the thermal conductivity of the polymer, $K_{polymer}$ and the air, K_{air}, according to the Lewis-Nielsen equation:[26]

$$\frac{K_{bed}}{K_{air}} = \frac{1 + AB}{B\psi\phi} \tag{6.13}$$

* In reality, the assumption of constant air temperature is not correct.

where $A = k_E - 1$, $B = \dfrac{K_{\text{polymer}}/K_{\text{air}} - 1}{K_{\text{polymer}}/K_{\text{air}} + A}$ and $\psi = 1 + \dfrac{(1-P)\,\phi}{P^2}$. Here, k_E is the Einstein coefficient, with a typical value of 2.5 for near-spherical particles and random packing, P is the maximum packing fraction of the powder, and ϕ is the volume fraction of polymer in the bed, $\phi = (\rho_{\text{bulk}} / \rho_{\text{polymer}})$. The effect of bulk density on the relative thermal conductivity of a powder bed is seen in Figure 6.7,[27] where the ratio of thermal conductivity of air to polymer is 0.2. Typically, the thermal conductivity of untamped powder ranges from 20 to 50% of that of the polymer. The heat capacity of the powder bed is given as:

$$c_{p,\text{bed}} = (1 - \phi)c_{p,\text{air}} + \phi c_{p,\text{ polymer}} \tag{6.14}$$

As a first approximation, the thermal diffusivity of the static powder bed can be considered only weakly dependent on the powder bulk density. Its value is approximately the same as the thermal diffusivity value of the polymer over the typical untamped powder bulk density range. This approximation is not valid for flowing powder, whether in steady-state circulation flow or avalanche flow. For flowing powders, the thermal diffusivity decreases by a factor of up to 10.

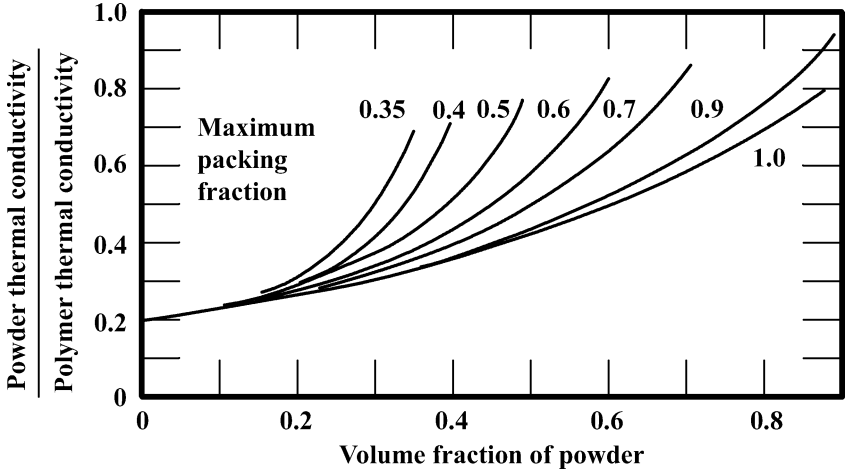

Figure 6.7 Effect of powder bulk density on thermal conductivity of powder,[27] redrawn, with courtesy of John Wiley & Sons, London

6.9 Tack Temperature

It was noted earlier that certain powders, called Coulomb powders, do not flow well. Frictional forces between individual powder particles, and between powder particles and the mold surface, are sufficiently great to allow these powders to adhere to one another and to the mold surface. Coulomb forces increase with increasing temperature. Coulomb forces between particles and the mold surface decrease with low-friction mold treatments. As the mold heats, the powder bed and the mold cavity air are also increasing in temperature. Two changes in the process are seen at about the same temperature. First, the elevated air temperature and the continuing particle-to-particle contact smooths or polishes the powder surface in a fashion similar to that observed in certain grinding operations. This implies that asperities and projections become more rounded and the polymer particles tend to flow better. However, the polymer surface also begins to soften. Since the mold surface temperature is usually higher than that of either the bulk powder or the mold cavity air, the powder particles tend to stick preferentially to the mold surface. However, agglomeration of powder particles is also common during this period in the heating cycle. For viscous flow polymers, Van der Waals force, electrostatic force, and solid and liquid bridges are the primary means of agglomeration.

The temperature at which powder particles tend to stick to solid surfaces and to one another is called the *tack temperature*. This temperature is generally considered to be the temperature where the adhesion forces between solid surfaces exceed the gravitational forces or the particle-to-particle and particle-to-mold surface impacting forces.[28] The bonding force for a liquid bridge between two powder particles is the sum of capillary suction pressure and surface tension of the liquid. The bonding force is strongly dependent on the area of the liquid bridge region. Thus, one might expect bonding forces between cubes to be greater than those between spheres, and bonding force between an irregular particle and the planar mold surface to be greater than that between two irregular particles.

For amorphous polymers such as PMMA and PC, the tack temperature is about equal to or slightly greater than the polymer glass transition temperature. For crystalline polymers such as LDPE and PP, the tack temperature is about equal to the polymer melt temperature. Table 6.4 gives some representative tack temperature values.

As discussed earlier, mold, cavity air, and polymer temperatures can now be measured using thermocouples with the signals being transmitted via FM

Table 6.4 Tack Temperature for Rotational Molding Polymers

Polymer	Melt Temperature, °C	Glass Transition Temperature, °C	Tack Temperature, °C*	Kink Temperature, °C
LDPE	120±1	—	115±5	NA
MDPE	125±5	—	120±5	100
HDPE	130±1	—	130±5	NA
PP	165±5	—	155±5	120
Nylon 6	225	—	NA	175
APET	—	80	100±5	110
GPPS	—	105	110±5	NA
MIPS	—	105	120±5	NA
ABS	—	105	125±5	117
PMMA	—	105	105±5	NA
PC	—	155	160±5	155

* Measured by blowing -35 mesh polymer powder against a hot plate held in a vertical position

to a receiver outside the oven and cooling chamber environments.[29] One example of the measured time-dependent temperatures is given as Figure 6.8. The first observed change in the slope of the air temperature is an indication that powder is beginning to adhere to the mold surface. As discussed below, the adhering powder first forms a porous three-dimensional matrix with thermal properties not much different than the thermal properties of the discrete polymer particles in the static bed. The adhering, melting powder then acts as a heat sink and an insulating layer against the inner mold surface, thus retarding the rate of energy transfer to the cavity air, and to the powder bed, as well. The measured effect is a well-defined drop in the measured rate of increase of mold cavity air temperature. The temperature at which this almost-abrupt change occurs is called the *kink temperature*. As seen in Table 6.4, the kink temperature for a given polymer agrees reasonably well with its tack temperature.

It is generally accepted then that for initial particle-to-mold and particle-to-particle adhesion, the surface temperature of the particle must be approximately equal to the melt temperature for a crystalline polymer or the glass transition temperature for an amorphous polymer.

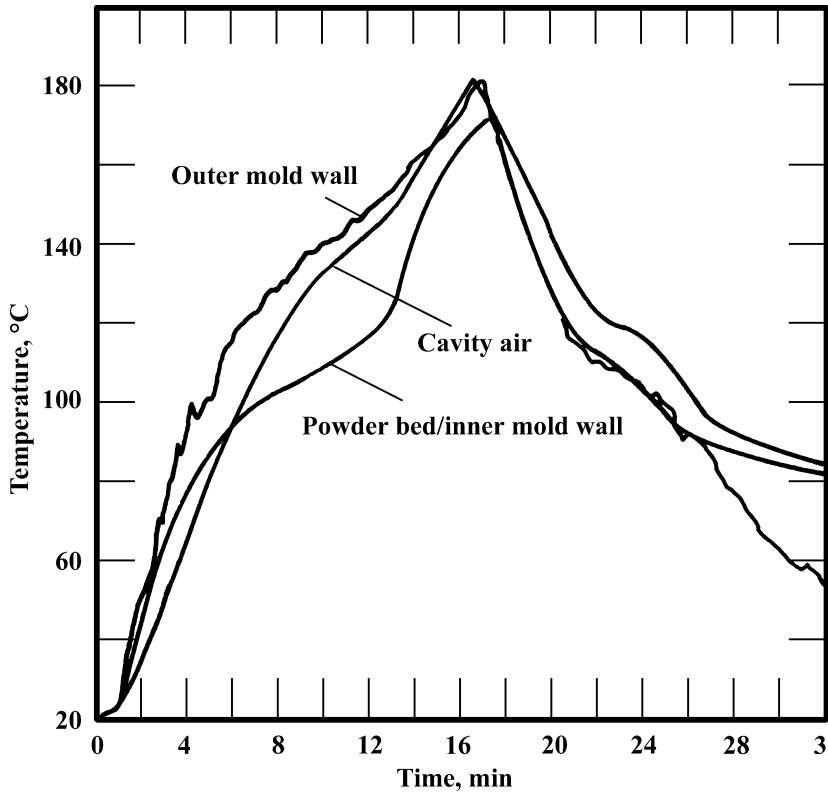

Figure 6.8. Time-dependent temperatures at various points in the molded part

Note here that this analysis is concerned only with solid-solid bonding forces that are sufficient to inhibit particle separation and bulk flow. The building of a monolithic structure of these particles through coalescence is discussed in detail below.

The second change in the measured rate of increase in mold cavity air temperature is associated with the completion of the coalescence phase of the process and is discussed below.

6.10 Mold Cavity Air Heating Prior to Powder Adhesion to Mold Surface

The temperature differential across the mold wall is quite small for traditional rotational mold materials. Earlier, it was also noted that the mold cavity air tem-

perature appears to lag behind the inner mold surface temperature in a near-linear fashion during the early stages of heating, prior to reaching point A on Figure 6.2. For most transiently responding systems, any time-dependent temperature can be written in terms of a transient effect and a steady-state effect:

$$T(\theta,0) - T(\theta,X) = F_1(G,M;\ \theta) + F_2(G,M) \tag{6.15}$$

Where $F_1(\ )$ is the transient effect and $F_2(\ )$ is the steady state effect. G and M represent geometric parameters and material parameters, respectively. For long times, the temperature difference is given only in terms of time-independent terms:

$$T(\theta,0) - T(\theta,X) = F_2(G,M) \tag{6.16}$$

If the mold surface is exposed to a step-change in temperature, then the mold cavity air temperature after the initial time is given as:

$$T_{mc} = T_{im} - x/2K' \tag{6.17}$$

Where T_{mc} is the mold cavity temperature, T_{im} is the inner mold temperature, x is some representative thickness and K' is some representative thermal conductivity. This thermal offset is observed in mold cavity air temperature measurements, such as Figure 6.1. It is expected that if the powder bed is particularly deep or if the effective thermal conductivity of the powder is particularly low, the effective resistance to heat transfer to the mold cavity air will be high and its temperature will substantially lag behind that of the inner mold surface temperature.

6.11 Bed Depletion

The powder bed decreases in volume as particles tack to the mold wall and then to themselves. Several changes in the nature of the free powder in the bed may be observed as the bed decreases. As the free powder increases in temperature, the Coulomb forces increase, allowing substantial agglomeration. The nature of the powder bed may change, from steady-state slip flow or circulation to the periodic avalanche flow behavior. Part of the reason for this is the now-irregular surface over which the powder is flowing and part is the increasing effect of Coulomb forces. The transient heat transfer nature may change as well, for two reasons. First, the agglomerated particles present a much larger radius for heat transfer. Since the Fourier number, which is a measure of the rate of conduction heating, is inversely proportional to the square of the particle radius, the effect is a slowing of the heating rate. And, energy from hot oven gases must now be transmitted not

only through the mold but also through a coating of stuck-together polymer particles. With amorphous polymers the energy absorbed by the polymer is nearly linear with temperature (Figure 6.9). With crystalline polymers, on the other hand, substantial energy is needed to melt the powder particles, once they tack to the mold or to other particles. Again as seen in Figure 6.9, discussed in more detail later, it takes nearly twice as much energy to heat polyethylene, a crystalline polymer, to its molten state as to heat acrylic, an amorphous polymer, to the same temperature. This added thermal resistance slows the rate of heating of the remaining polymer powder. The effect is manifested by an increase in the difference between the mold surface temperature and the mold cavity air temperature, Figure 6.1.

One approach to steady-state circulating powder bed energy absorption follows a segment of powder bed sequentially through transient heating, then mixing to produce a uniform temperature, then transient heating again, until the segment reaches tack temperature and beyond.[2] Heating cycle time prediction seems reasonable. This model is discussed below.

6.12 Particle Coalescence

The adhesion of a powder particle on a mold surface also depends on the surface area of the particle in contact with the surface. Particles with relatively flat areas, such as disk-like and squared-egg particles, should adhere more readily than particles with point contact, such as spheres. Similar characteristics hold for particle-to-particle adhesion. Coordination numbers or the numbers of touch points on spherical particles for different packing arrangements are found in Table 3.4. In that Table, the number ranges from 6 for cubic to 12 for rhombohedral. From experimental packing studies, the coordination number range for irregular particles is about the same (6 to 14 or so), with a mean of 10 or so. Of course, adhesion is only the first step toward the production of a monolithic particleless structure. The interface between the adhering surfaces, either polymer-to-polymer or polymer-to-mold, forms a polymeric neck or bridge that grows in radius with time. The formation and growth of the neck and hence the three-dimensional, continuous web-like polymeric structure is called "sintering," after a parallel effect seen in powder metallurgy or more recently and more correctly, "coalescence."*

* Although the term "sintering" has been used in the rotational molding literature to describe the formation of a monolithic polymeric structure from powder, it has been pointed out that the term is usually restricted for a consolidation process that takes place below the polymer melting temperature. In rotational molding, the consolidation process always takes place above T_g and above T_m for crystalline polymers and is therefore called "coalescence."

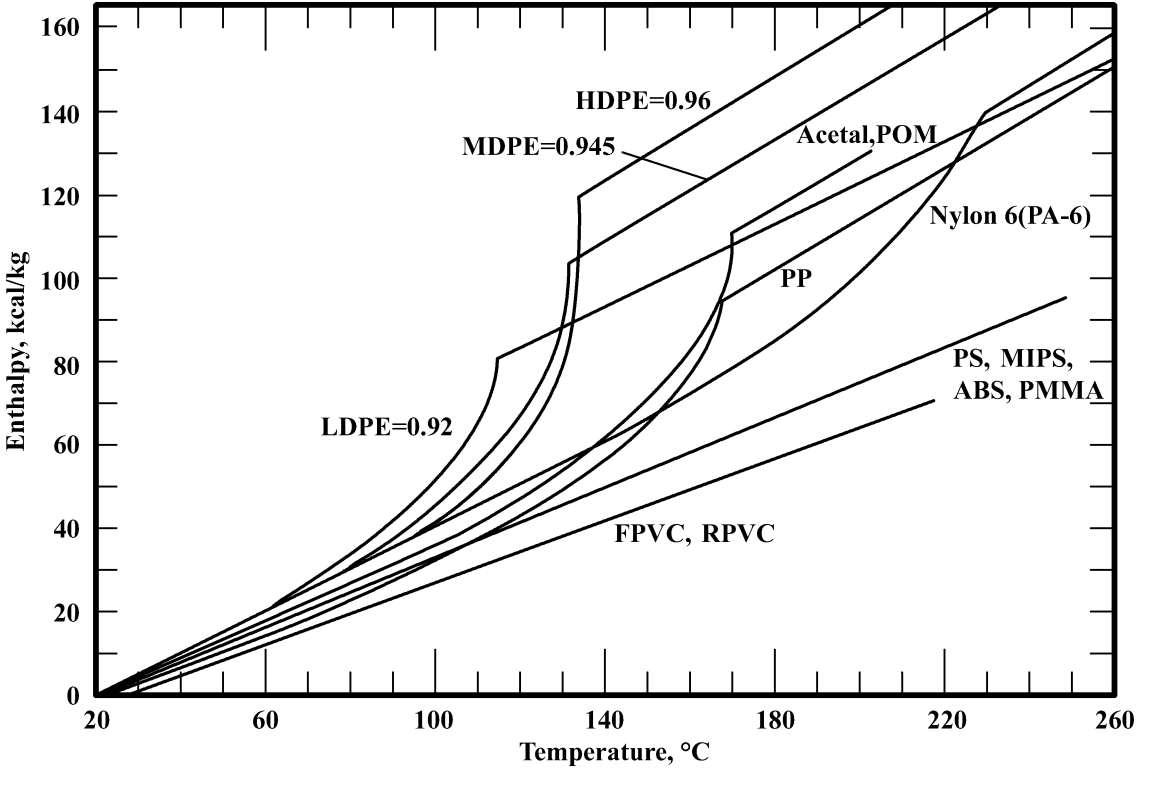

Figure 6.9. Enthalpies of several polymers,[64] redrawn, with courtesy of Hanser Verlag, Munich

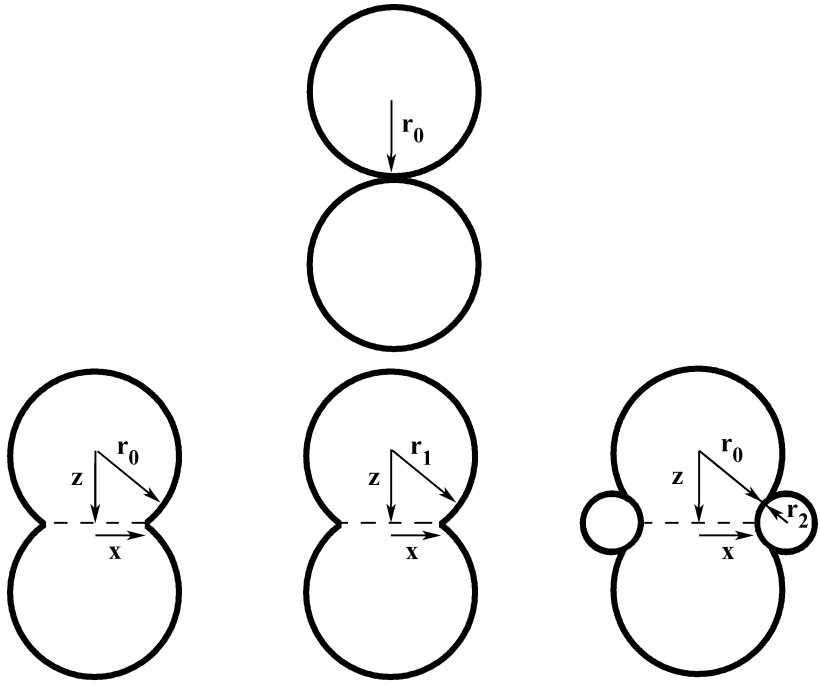

Figure 6.10 Geometric models for particle-to-particle neck growth,[32,33] redrawn, with courtesy of John Wiley & Sons, London

There are many experimental and theoretical studies of polymer particle coalescence, beginning with Kuczynski's 1949 adaptation of Frenkel's 1945 work on coalescence of identical glass spheres.[30,31] Sintering and coalescence studies continue to examine the mechanism by which one particle, albeit dumb-bell in shape, is formed from two particles.[32,33] The general coordinates of the model are shown in Figure 6.10. The time- and temperature-dependent formation of the neck region between two coalescing particles is compared with the bulk polymer temperature in Figure 6.11.

Most models assume that the driving force for neck formation is viscous response to surface tension. The general form for necking models is:

$$x_{\text{neck}} = \kappa r^{\alpha}_{0} \theta^{\beta} \tag{6.18}$$

where x_{neck} is the thickness of the web, r_0 is the radius of the sphere, κ is a proportionality constant that includes surface tension, viscosity, modulus, and any other polymer properties that might be significant. α and β are functions

of the deformation mechanism, as detailed in Table 6.5. θ is time. For most polymers, neck growth is considered to be zero-shear Newtonian in behavior. As a result, the neck should grow according to:

$$x_{\text{neck}} = \kappa\sqrt{r_0\theta} \quad \text{or} \quad x_{\text{neck}} / r_0 = \kappa\sqrt{\theta / r_0} \tag{6.19}$$

Another way of looking at this expression is to take the time-derivative of the second equation:

$$\frac{d\left(x_{\text{neck}} / r_0\right)}{d\theta} = \kappa r_0^{\alpha-1}\theta^{\beta-1} = \kappa r_0^{-1/2}\theta^{-1/2} \tag{6.20}$$

This equation illustrates two important aspects of coalescence. The first is that the rate of growth of the neck ratio, $d(x_{\text{neck}}/r_0)/d\theta$, is inversely proportional to the square root of the powder particle radius. Thus the smaller the particle is, the more rapidly it coalesces. And the second is that the neck growth ratio is inversely proportional to the square root of time. Therefore, the rate of neck growth decreases with increasing time. In other words, if

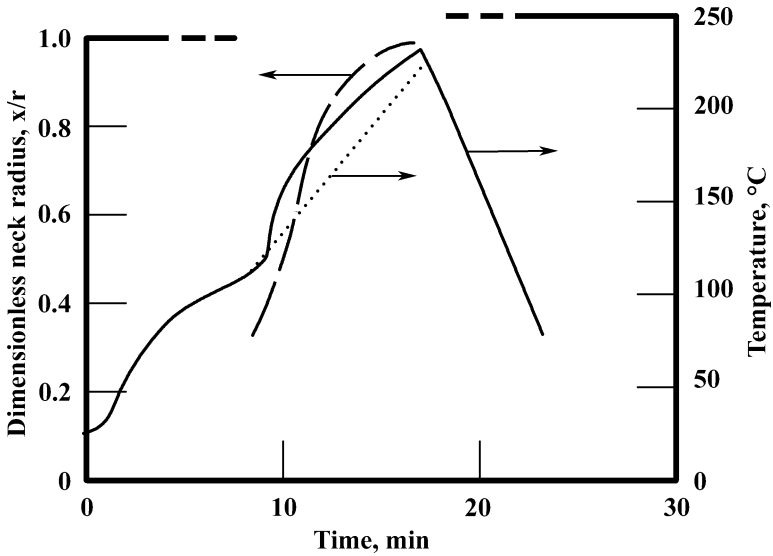

Figure 6.11 Comparison of neck development and coalescence temperature with the rotational heating cycle,[32] redrawn, with courtesy of John Wiley & Sons, London. Solid line, mold temperature profile; dotted line, polymer sintering temperature; dashed line, experimental neck radius

growth does occur, it will grow most rapidly immediately after first contact. Note however that this model is designed for equilibrium Newtonian viscous-only neck growth between two equal size spheres in elastic contact, where the coordination number is one.

Table 6.5 Neck Growth Coefficients

Mechanism	**α**	**β**
Newtonian flow	1/2	1/2
Elastic deformation	2/3	0
Bulk diffusion	2/5	1/5
Surface diffusion	3/7	1/7
Evaporation/condensation	1/3	1/3

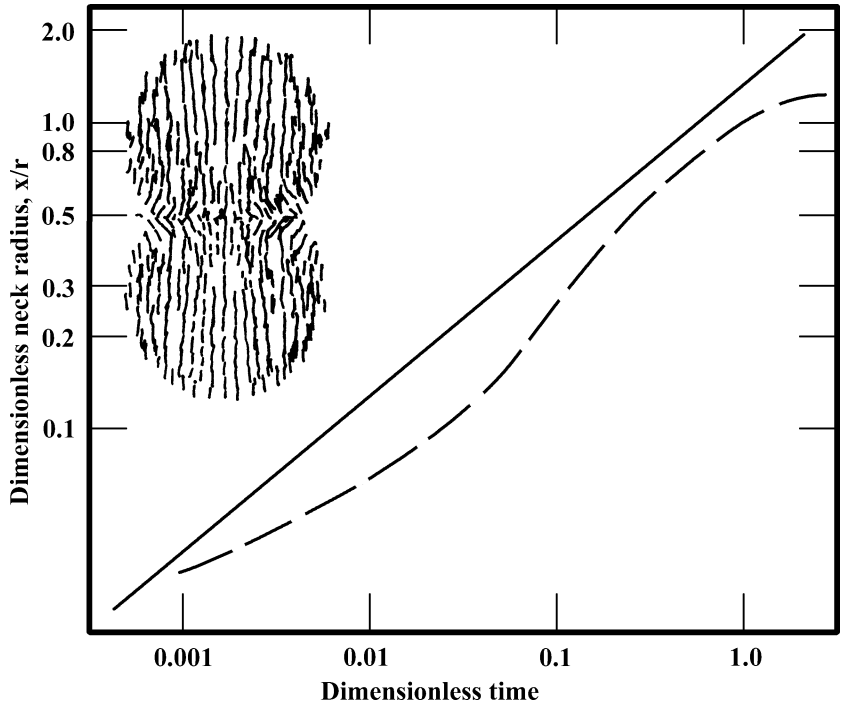

Figure 6.12 Comparison of Frenkel theory (solid line) with FEA model (dashed line), showing slower growth at short times,[34] redrawn, with courtesy of John Wiley & Sons, London

Three approaches are proposed to determine the polymer properties needed to determine neck growth rate. These are the Newtonian viscous-only, Hertzian elastic, and viscoelastic models.[32,33]

Newtonian Viscous-only Growth Rate. The oldest approach assumes that coalescence is driven entirely by surface tension. In order to achieve a force balance at the interface, Frenkel assumed a velocity distribution identical to that for a uniaxial compression of a Newtonian cylinder of radius x_{neck}. This assumption yields the following equation, sometimes referred to as the Frenkel-Eshelby equation:

$$\frac{x_{neck}}{r_0} = \sqrt{\frac{\gamma\,\theta}{\mu r_0}} \tag{6.21}$$

Here γ is surface tension and μ is the Newtonian viscosity. The Newtonian viscous-only neck growth rate is therefore:

$$\frac{d\left(x_{neck}/r_0\right)}{d\theta} = \frac{1}{2}\sqrt{\frac{\gamma}{\mu} r_0^{-1/2}\theta_0^{-1/2}} \tag{6.22}$$

In other words, $\kappa \equiv \sqrt{\gamma/4\mu}$. Recently, finite element analysis has shown that the exact mathematical solution shows a neck growth rate that is slower than that predicted by the Frenkel-Eshelby equation, Figure 6.12.[34] FEA also shows that the growth rate is nonlinear. Experimental evidence supports the nonlinear FEA model, as seen in Figure 6.13 for LDPE.[35]

Elastic Hertzian Growth. This approach considers growth at the interface solely as the result of contact deformation between elastic bodies. The equilibrium neck dimension is given entirely in terms of the polymer shear modulus G and its Poisson's ratio, ν:

$$x_{neck}^{\,3} = \frac{9\pi\sigma(1-\nu)}{4G} r_0 \quad \text{or} \quad \frac{x_{neck}}{r_0} = \left[\frac{9\pi\sigma(1-\nu)}{4G}\right]^{1/3} r_0^{-2/3} \tag{6.23}$$

The important aspect of the elastic neck dimension is that it is independent of time, since this is an elastic-only equation. The size of the elastic neck increases with increase in surface tension, as is the case with viscous-only growth rate. But it also increases with decreasing modulus. Thus, one would expect that the elastic neck dimension should be greater with polypropylene, say, than with polycarbonate.

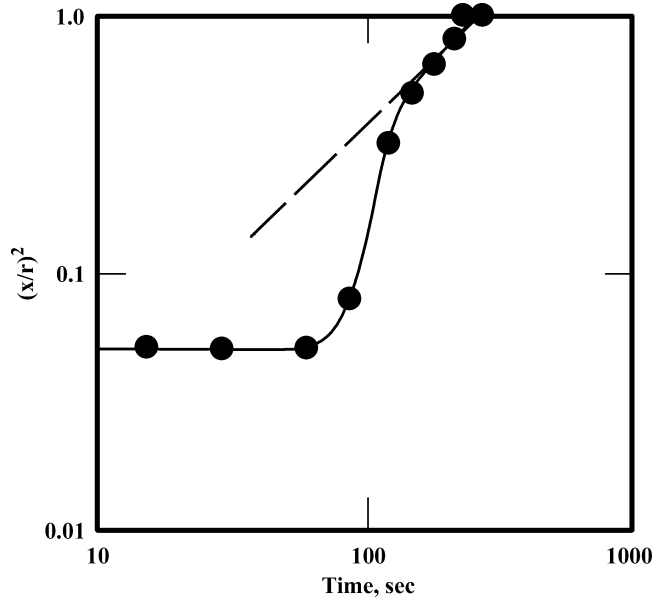

Figure 6.13 Experimental neck growth of LDPE (solid circles) compared with Frenkel model (dashed line)[35]

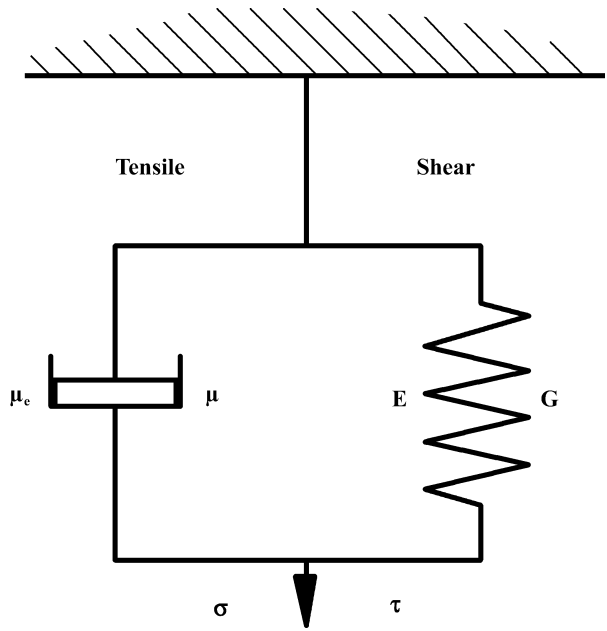

Figure 6.14 Voigt-Kelvin mechanical model for tensile and shear loads,[36] redrawn, with courtesy of Hanser Verlag, Munich

Viscoelastic Growth Rate. Viscous-only flow at the neck site is dissipative. Elastic deformation is conservative and reversible. Since the polymer behavior at the neck site is probably related to creeping flow, elements of both types should be expected. One approach is linear viscoelasticity, where the viscous and elastic elements are modeled as springs, representing elastic behavior, and dashpots, representing viscous behavior. A simple parallel spring-and-dashpot, Figure 6.14,[36] adequately represents creep flow. The equation describing the model response to applied load is given as:

$$\dot{\varepsilon} = \left(\frac{E}{\mu_e}\right)\varepsilon_T = \frac{\sigma}{\mu_e} \tag{6.24}$$

where σ is the applied stress, E is the elastic modulus, μ_e is the elongational Newtonian viscosity and ε_T is the total displacement. The overdot represents the rate of change of the property with time. Now this equation is applied at the neck site, with elongation representing the growing neck radius. Under uniformly applied load, presumably driven by surface tension, $\sigma = \sigma_0$ and $\dot{\sigma} = 0$. The equation then becomes

$$\varepsilon = \left(\frac{\sigma_0}{E}\right)\left(1 - e^{-\theta E/\mu_e}\right) \tag{6.25}$$

Note that this expression shows neck growth that is asymptotically increasing to a fixed value. When $\theta \rightarrow \infty$, $\varepsilon \rightarrow (\sigma_0/E)$, the rate of neck growth exponentially approaches zero:

$$\frac{d\varepsilon}{d\theta} = \left(\frac{\sigma_0}{\mu_e}\right) e^{-\theta E/\mu_e} \tag{6.26}$$

While this model does not mirror the Newtonian viscous-only model, where the rate of neck growth is proportional to the reciprocal square root of time, it does show that this very simple linear viscoelastic model is quite time-dependent in a similar fashion. More importantly, this viscoelastic model incorporates both elastic (E) and viscous (μ_e) elements in the time-dependency. The term μ_e/E is sometimes called the first order time constant for a linear viscoelastic polymer, and is written as:

$$\lambda = \mu_e/E \tag{6.27}$$

A more complex four-parameter model incorporates a parallel spring-and-dashpot and a series spring-and-dashpot, in series. The response of this model to a constant stress is shown in Figure 6.15.[36] As is expected the elastic response to applied stress is seen immediately. The viscous response then produces the major deformation that continues until the applied stress is removed. In the case of rotational molding, the applied stress is not removed during the coalescence phase of the process.

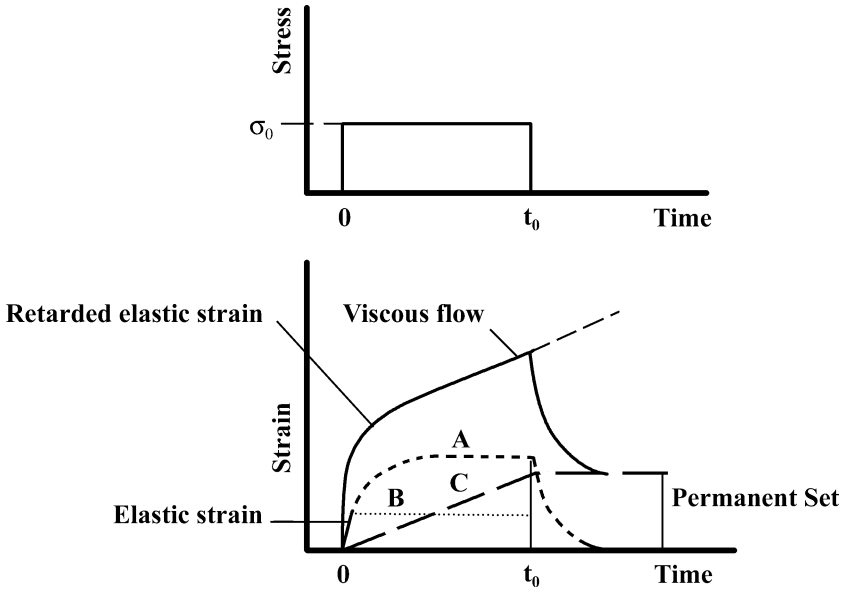

Figure 6.15 Response of four-parameter model to step change in applied load,[36] redrawn, with courtesy of Hanser Verlag, Munich

As noted, the viscoelastic time constant, λ, is a measure of the polymer response to physical changes. Coalescence and, as noted below, bubble dissolution, are time-dependent phenomena. One measure of the relative response of the polymer to these effects is the Deborah number, $De = \lambda/\theta = \mu/\theta E$, where θ is some measure of process time. When $De << 1$, the polymer tends to behave elastically or conservatively to physical changes. When $De >> 1$, the polymer tends to behave viscously or dissipatively to physical changes.[37]

Recently, an approach using creep compliance has been proposed to help resolve the roles of the elastic and viscous contributions during coalescence.

The compliance, $J(\theta)$, is given as:

$$J(\theta) = \varepsilon_{ij}(\theta)/\sigma_{ij} = J_r(\theta) + \left(\frac{\theta}{\mu}\right) \tag{6.28}$$

where $J_r(\theta)$ is the recoverable or elastic portion of the creep compliance. Compare this expression with the simple linear viscoelastic model given earlier. It has been proposed that $J(\theta)$ exhibits a rapid rise with time, begins to plateau, and eventually approaches an asymptote in what is called the thermal time (Figure 6.16).[38] It is believed that at very short times, the polymer interface behaves in a rubbery elastic fashion. When $\theta > J_{neck}\mu_0$, considered the time at which viscous and recoverable contributions are equal, the material response shifts from rubbery elastic to Newtonian fluid-like. In Figure 6.16, this is shown as the plateau region. It is also seen as the region above the retarded elastic strain in the four-parameter model. Accordingly, the plateau region is established before significant viscous flow occurs. As a result, retarded elastic strain, sometimes

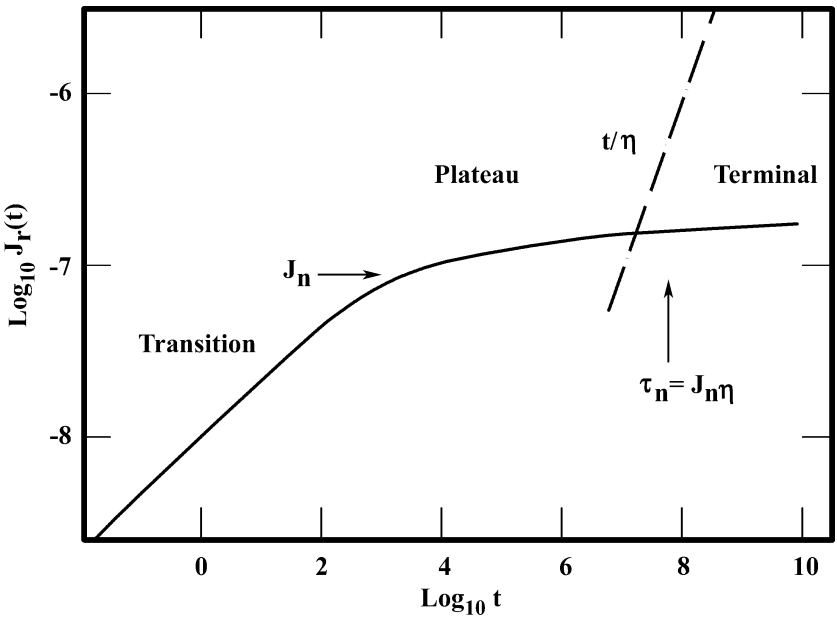

Figure 6.16 Recoverable creep compliance for neck growth,[38] redrawn, with courtesy of John Wiley & Sons, London

called quasi-elastic deformation, is apparently an important component of neck growth.

The Hertzian elastic component given earlier can now be written in terms of creep compliance as:

$$\frac{x_{\text{neck}}}{r_0} = \left[\frac{9\pi\sigma(1-\nu)J_{\text{neck}}}{8r_0}\right]^{1/3} \tag{6.29}$$

The strong dependency of the neck ratio on initial particle radius is very important. For very small particles, in the range of 1 to 10 μm in dimension, the elastic effects dominate the neck formation. For particles on the order of 100 μm in dimension, the elastic effects represent only a small fraction of the total neck formation. Figure 6.17 illustrates the time-dependent growth of r_0 = 130 μm acrylic beads at 132°C.[39] As is apparent, the Newtonian viscous-only model does not accurately predict initial neck growth. It takes about six decades of time to achieve a 1000% increase in

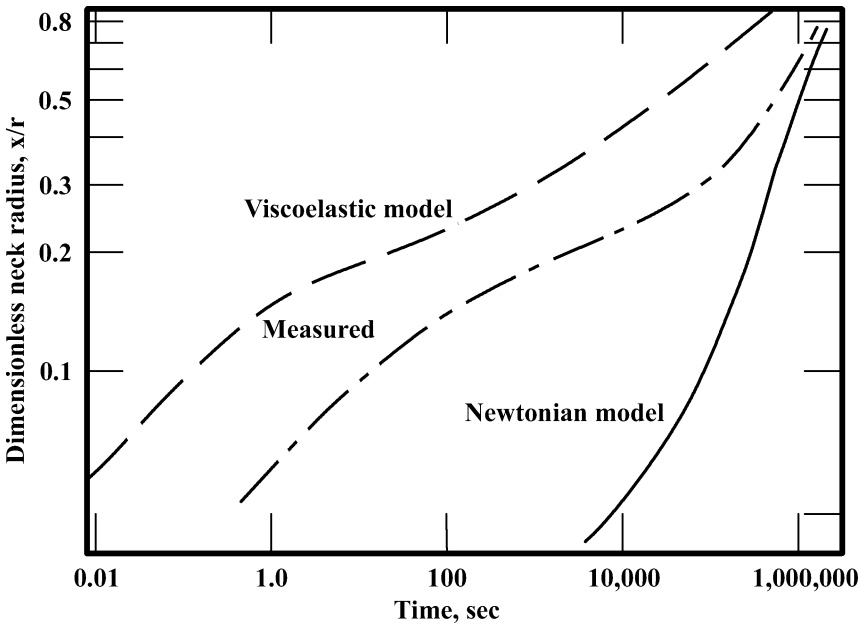

Figure 6.17 Observed neck growth compared with Newtonian and viscoelastic models,[39] redrawn, with courtesy of John Wiley & Sons, London

neck ratio dimension. The Newtonian model predicts that it should take only two decades of time, an error of a factor of about 1000. Only when x_{neck}/r_0 approaches about 0.5 do the experimental data and theory begin to agree. The relative shape of the experimental data mimics the transition and plateau regions of Figure 6.16. It is concluded that nearly half of the neck growth is directly identified with quasielastic deformation or retarded elastic strain.

One way of melding these two effects is to simply add them, as:

$$\frac{x_{\text{neck}}}{r_0} = \left[\frac{9\pi\sigma(1-\nu)\ J_r(\theta)}{2r_0}\right]^{1/3} + \left(\frac{\gamma\,\theta}{\mu_0 r_0}\right)^{1/2} \tag{6.30}$$

The dashed line in Figure 6.17 was calculated from this equation, which incidentally does not contain any adjustable constants. While the simple function does not yield agreement with the data, the relative shape outlined by the dashed line follows the experimental data quite well.

Another viscoelastic model, based on the Frenkel equation,[40] demonstrates that the coalescence rate decreases with increasing elastic effect. Since both viscosity and melt elasticity decrease rapidly with increasing temperature, the rate of coalescence must increase as molding continues.

In summary, the key elements of coalescence focus on the rubbery elastic behavior of the polymer in the very early stage of neck growth and viscous, dissipative behavior at later stages. For viscoelastic polymers with very high elastic moduli, early neck growth may be severely inhibited, potentially to the point where powder particles are tacked together but remain so throughout the rest of the molding process. This results in a porous monolithic structure, rather than a fully densified structure.

6.13 Densification

The bulk effect of particle-to-particle coalescence is the formation of a three-dimensional web-like network, in which both the polymer and the mold cavity air are continuous phases. The energy transmission between the mold inner wall and the mold cavity air is now reduced by the resistance through the network. In an earlier section, the thermal resistance through the loose powder bed was related to an effective thermal diffusivity,

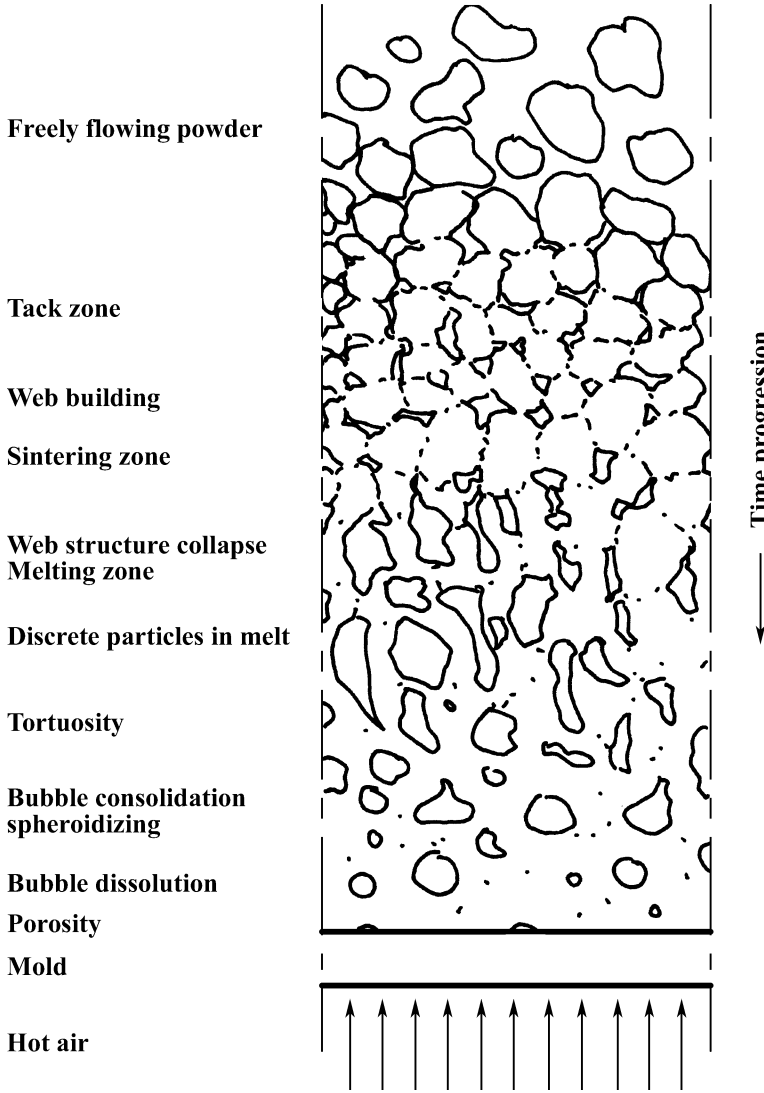

Figure 6.18 Schematic showing progression from loose powder through coalescence, bubble dissolution and, densification,[41] redrawn, with courtesy of John Wiley & Sons, London

$\alpha_{\text{effective}}$, being the ratio of the thermal conductivity of the powder bed to the powder bed density and heat capacity. This property holds for the network structure as well. The relative effect is seen in Figure 6.1, as a retardation in the rate of heating of the mold cavity air. This experimental observation was mathematically predicted in the 1970s. As the neck dimension increases, particle individuality disappears and the air in the lattice structure forms tortuous tubes typically having orientations at right angles to the mold surface. Figure 6.18 is a schematic of coalescence and densification.[41] Three mechanisms have been proposed for the densificiation step.

Capillary Action. The earliest proposed mechanism[42] considered capillary action or the wicking of a viscous-only polymer into the void region between coalescing particles. The time required to fill a void *z* units in depth and *r* units in radius is given by:

$$z^2 = \frac{r}{2}\int_0^{\theta} (\gamma / \mu)\, d\theta \tag{6.31}$$

If the surface tension, γ, and the Newtonian viscosity, μ, are considered to be either constant or decrease in value at about the same rate, then the capillary filling rate is given as:

$$\frac{z}{r_0} = \sqrt{\frac{\gamma\,\theta}{2\mu\; r_0}} \quad \text{or} \quad \frac{d(z/r_0)}{d\theta} = \sqrt{\frac{\gamma}{8\mu r_0 \theta}} \tag{6.32}$$

The capillary rate of void filling is dependent on the same polymer properties as the neck growth rate, and is proportional to the void radius and time in the same manner as the neck growth rate. It has been proposed that void filling can be predicted in the same manner as neck growth for viscoelastic liquids as well.

Gross Network Collapse. Another mechanism focuses on network collapse. The collapsing mechanism occurs when the polymer exceeds its melt temperature and its melt strength is insufficient to resist the applied forces, being primarily the weight of the polymer bed and the surface tension. Experimentally, when polymer powders are melted in a static fashion, the liquid-solid interface is quite easily observed and measured (Figure 6.19).[43] Except for localized, very short fingers that extend into the coalesced network, the melt front is quite planar to the mold surface. The measured bulk effect is a very regular decrease in the powder bed

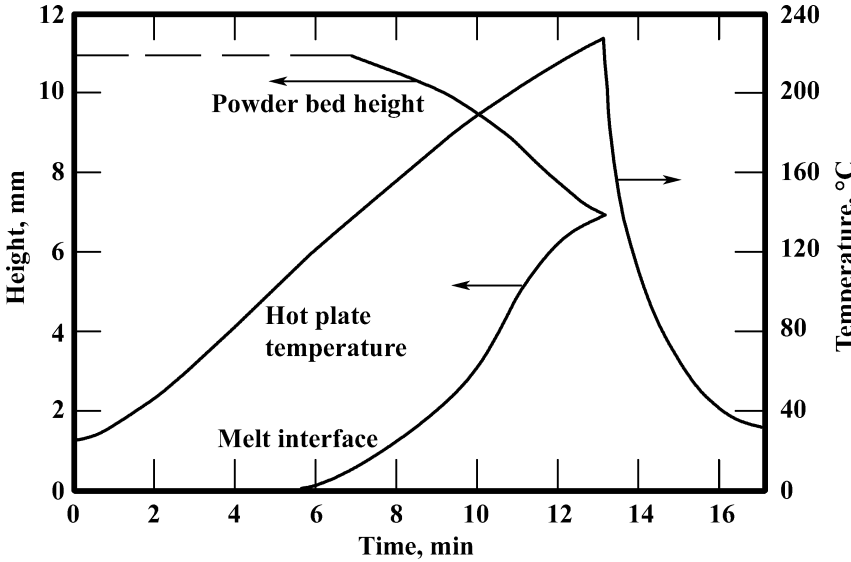

Figure 6.19 Bulk powder behavior — polyethylene under vacuum[43]

height, indicating that the network structure at the liquid-solid interface is preferentially being drawn into the melt, rather than the melt being drawn by capillary action into the network. Another interpretation is that the tacked-together powder structure weakens as it is heated. As a result, the powder columns simply collapse under their own weight. Experiments show that when the mold cavity is evacuated during densification, there are no bubbles in the molten pool. Experiments also show that when the powder bed and network are slowly heated in the presence of mold cavity air, there are relatively few bubbles in the molten pool. And when the powder bed and resulting network are rapidly heated in the presence of mold cavity air, there are many bubbles trapped in the molten pool. Bubble encapsulation is therefore the result of network collapse at a rate that prevents all the air from being pushed through the remaining network and loose powder bed ahead of the advancing melt front. As a result, the tortuous air tubes are transformed into discrete bubbles, that subsequently become tear drop-shaped or spherical. It has been proposed that the underlying mechanism for bulk air migration from the coalescing, densifying powder bed is the viscous or perhaps viscoelastic character of the polymer and not capillarity.[44] Figure 6.20 shows the relative effect of polyethylene melt index on the time-dependent bed densification.

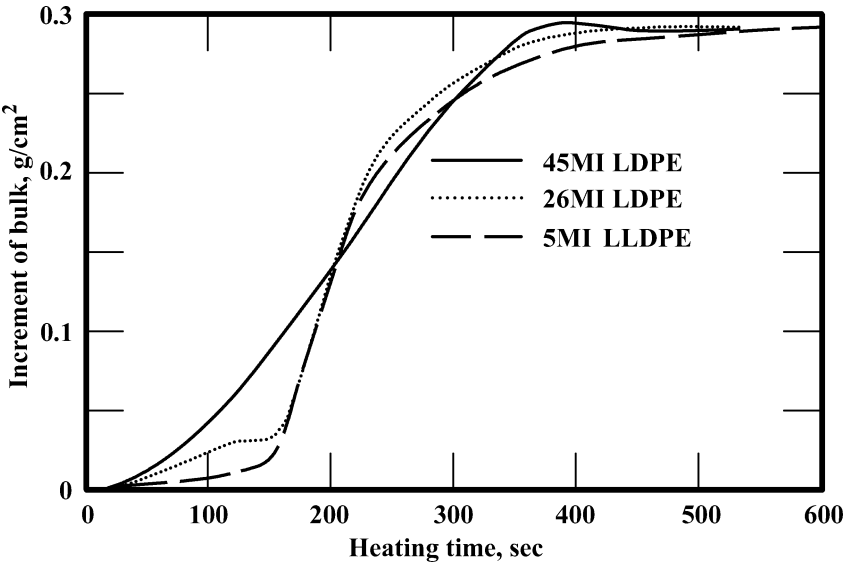

Figure 6.20 Effect of PE melt index on bed densification[44]

Air Solubility and Diffusion. A third mechanism deals with the disappearance of encapsulated bubbles. It has been proposed that in order for these bubbles to disappear, the air in these bubbles must diffuse into and be absorbed in the surrounding polymer.[45–48] The driving force is the differential pressure between the air in the bubble and atmospheric pressure, Rayleigh's equation:

$$\Delta P - \frac{2\gamma}{R} = 0 \tag{6.33}$$

where ΔP is the pressure above atmospheric, γ is surface tension, and R is the radius of the bubble. The equation for bubble growth in an inviscid medium is:

$$\rho\left[\frac{3}{2}\left(\frac{dR}{d\theta}\right)^2 + R\frac{d^2R}{d\theta^2}\right] = \Delta P - \frac{2\gamma}{R} \tag{6.34}$$

If the polymer can be considered as Newtonian viscous, the time-dependent change in bubble radius is given as:

$$\rho\left[\frac{3}{2}\left(\frac{dR}{d\theta}\right)^2 + R\frac{d^2R}{d\theta^2}\right] + \frac{4\mu}{R}\left(\frac{dR}{d\theta}\right) = \Delta P - \frac{2\gamma}{R} \tag{6.35}$$

where ρ is the polymer density. If the polymer is viscoelastic, the rate of change of bubble radius is given as:

$$\rho\left[\frac{3}{2}\left(\frac{dR}{d\theta}\right)^2 + R\frac{d^2R}{d\theta^2}\right] + \frac{4\mu}{R}\left(\frac{dR}{d\theta}\right) + 3\int_R^\infty \frac{\tau_{rr}}{r}dr = \Delta P - \frac{2\gamma}{R} \qquad (6.36)$$

The last term on the left represents the polymer elastic contribution to bubble collapse, where τ_{rr} is the normal stress difference. Bubble collapse in viscoelastic polymers may be either catastrophic to zero radius, oscillating to zero radius, or collapse to an equilibrium radius.[49,50] Four dimensionless groups that help define bubble behavior have been identified. The bubble Reynolds number, the ratio of inertial to viscous forces, is usually very small for polymers. The Weber number is a measure of the importance of surface tension on bubble collapse. Typically the Weber number is large for small bubbles. The Elastic number is a ratio of the melt elasticity to its viscosity. The Deborah number is the ratio of polymer viscoelastic response time to general process time. The Deborah number, De, is large for polymers with long molecular relaxation times. For purely viscous polymers, De = 0. For purely elastic polymers, De → ∞. For viscoelastic polymers, De > 0, and bubbles must eventually collapse to zero. For De = 1, bubbles collapse in oscillating fashion. The number of oscillations and the frequency of oscillations depend on the melt elasticity, viscosity, and initial bubble diameter. The equilibrium radius is the ratio of the initial pressure in the bubble to the polymer elastic modulus. The equilibrium radius decreases with increasing polymer melt elasticity.

When the initial bubble radius is slightly greater than the equilibrium radius, the elastic force is small and the bubble collapses only when the viscous force is very large. And then the bubble collapses slowly, probably oscillating while collapsing. When the initial bubble radius is much greater than the equilibrium radius, the bubble simply collapses catastrophically.

Since the internal air pressure exceeds the pressure in the bulk polymer, the concentration of air in the bubble necessarily exceeds that in the bulk polymer. Henry's law, which is operable for dilute solutions, states that gas solubility is proportional to applied pressure:

$$S = H \cdot P \qquad (6.37)$$

where S is solubility, in cm^3 (STP)/g atm, H is Henry's law constant and P is local pressure in atm.[51] Since the gas solubility is greater at the bubble/polymer

interface than in the bulk of the polymer, a concentration gradient exists, and therefore mass transfer occurs from the bubble into the bulk of the polymer. If the gas inside the bubble is considered to be ideal, the differential equation describing the rate of bubble extinction is given as:

$$c_g dR/d\theta = D(\partial c/\partial r)_{r=R} \tag{6.38}$$

One solution to the time-dependent bubble extinction equation is given as:

$$\frac{1}{R} = \frac{1}{R_0} + \frac{c}{R_0^2}\left[\frac{d\theta}{R_0} + \frac{2\sqrt{D\theta}}{\pi}\right] \tag{6.39}$$

where R_0 is the initial bubble radius, D is the mass diffusivity of air in the polymer, and c is the initial concentration of air in the bubble.[52,53] Recently, more thorough analyses of bubble dissolution have been presented.[46,65] For one case, air bubbles in polyethylene, the surface tension effect is substantially greater than the normal stress difference for most of the

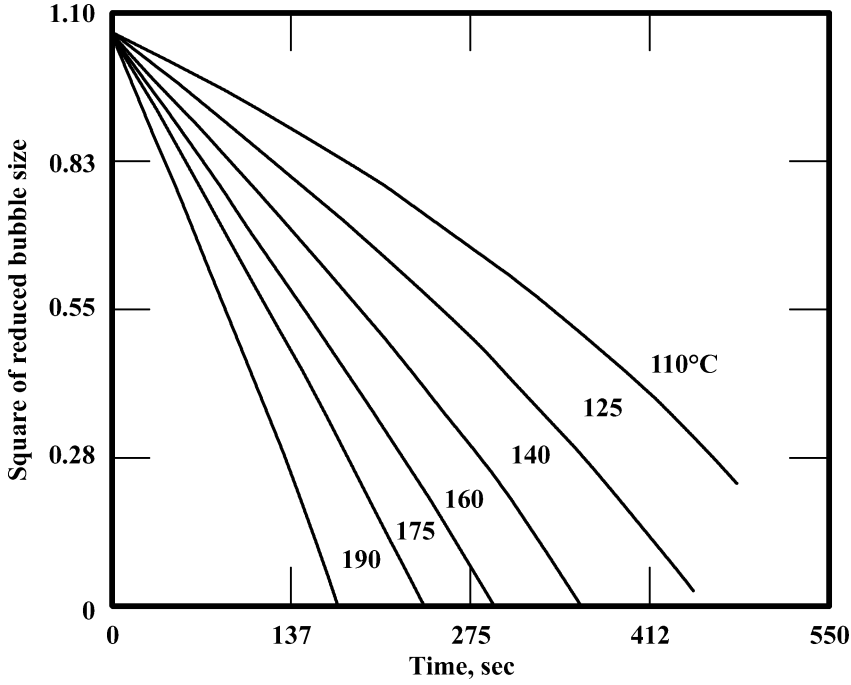

Figure 6.21 Time-dependent bubble size for HDPE. Lines drawn through experimental data[45]

bubble dissolution. Both effects increase dramatically as the bubble collapses to zero radius. The role of air diffusion from the collapsing bubble is important to the mechanics of bubble collapse. When diffusion is very rapid, small bubbles in a viscoelastic polymer collapse catastrophically and larger bubbles oscillate only a few times before collapse. When diffusion is very slow, bubbles always oscillate, regardless of the bubble dimension or viscoelastic nature of the polymer. Furthermore, if diffusion controls, bubbles do not collapse to zero radius, regardless of their initial size or the viscoelastic character of the polymer melt. The level of saturation of gas in the bulk polymer melt also influences the extent of bubble collapse. For example, if the polymer is initially saturated with air and the bubbles contain air, the diffusional concentration gradient will be small and the bubbles may not collapse to zero radius. Further, if there are many bubbles, the regions around these bubbles may be quickly saturated and the bubble collapse may be retarded or even stop. Figures 6.21 and 6.22 show excellent agreement between theory and experiment for air bubbles in HDPE at various isothermal mold surface temperatures.

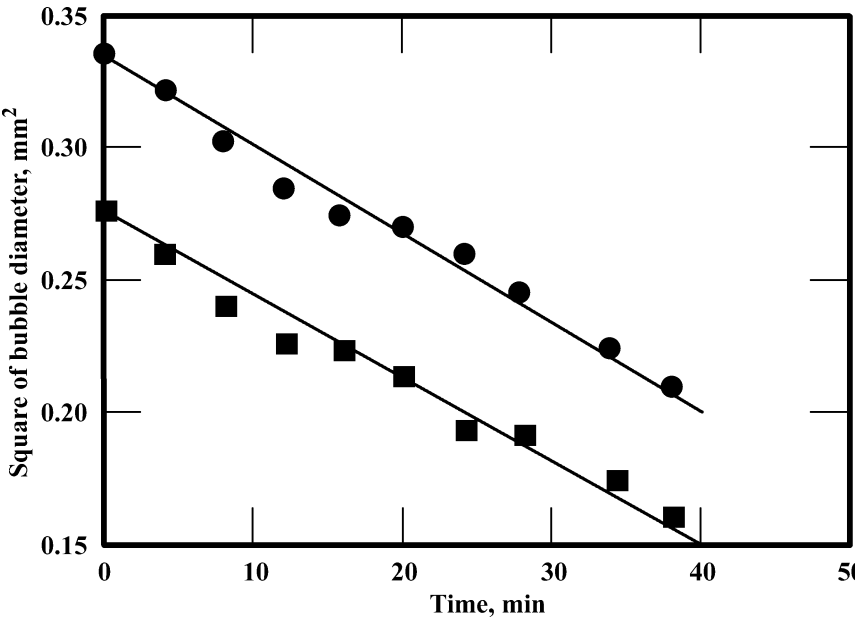

Figure 6.22 Time-dependent bubble extinction model and Spence's experimental data[46]

In practical rotational molding, air buoyancy in the polymer melt is not a factor. For static tests such as that shown in Figure 6.19, on the other hand, air buoyancy could be a factor, albeit a very slight one.[43]

It is apparent that the three mechanisms described above all act to densify the polymer structure. Both capillary action and air diffusion and solution show that the rate of densification is proportional to $\theta^{-1/2}$. And all three show that the rate of densification increases rapidly, probably exponentially, with increasing polymer temperature.

Although these mechanisms yield comparable results for static tests, the vagaries of the actual process make comparisons questionable. Keep in mind that the powder bed contacts only a portion of the mold surface at any instant. In-mold videography[54] shows that as the depleting powder bed flows across the powder already affixed to the mold surface, only a portion adheres to the tacky powder. In many cases, by the time the flowing powder returns, that portion that had adhered previously is tacky and may be almost fully coalesced into a discrete powder-free surface. This observed event would be best simulated in a static fashion by periodically applying thin layers of powder atop previously applied layers which are in contact with a hot plate that is increasing in temperature. Of course, the uncertainty of the process is that both the time and frequency of contact between the flowing powder and the affixed powder are unknown for most mold designs. Further, these aspects undoubtedly vary with location across the mold surface, with continuing depletion of the free powder bed, and with the changing nature of the temperature-dependent interparticle adhesion.

Having said that, it is apparent that the time of contact between the free powder bed and the fixed substrate is greatest when the powder first begins to stick to the mold surface. This implies that the thickest layer of powder affixed to the surface occurs in the beginning of the powder laydown. If the periodicity at any point is fixed by the rotation of the mold and if the rates of coalescence and densification do not dramatically increase with increasing temperature between periods of bed flow, then the greatest amount of porosity should occur at the beginning of powder laydown onto the mold, or in the polymer layer nearest the inner mold surface. Particle size segregation is an additional factor.

Finer particles should fluidize more than coarser particles. As a result, coarser particles should be preferentially at the bottom of the rotating

powder bed and should therefore contact the hot mold surface more frequently than finer particles. However, certain experiments prove the contrary. In the 1960s, decorator acrylic globes were manufactured using a mixture of powder and pellets. The powder coated the mold first, with the pellets adhering to the molten polymer. The product had a smooth exterior surface and a roughened interior surface. Recently, this experiment has been repeated with fine black polyethylene powder and coarse natural polyethylene powder of the same molecular weight. When a small amount of fine powder was used, the powder only partially coated the mold surface prior to coalescence of the coarser powder.* When the ratio of black fine powder to coarse natural powder was increased, the final part showed a distinct black polymer layer at the outer part surface and a distinct natural polymer layer at the inner part surface. In another study in a double-cone blender,[112] at a fill level of, say, 25%, the larger particles segregated to the center and the finer particles to the outsides. At a slightly lower fill level, the finer particles segregated to the center. And at a fill level in between, the finer particles migrated to one side and the coarser particles to the other. Once one of these patterns is established, it requires heroic measures to disturb it.

6.14 Phase Change During Heating

As noted, crystalline polymers such as polyethylenes, nylons, and polypropylenes, represent the majority of rotationally molded polymers. As seen in Figure 6.9,** crystalline polymers require substantially more energy to heat to fusion temperatures than do amorphous polymers such as styrenics and vinyls. Thermal traces during heating rarely show abrupt changes in the polymer heating rates. There are two reasons for this. First, crystalline polymers typically melt over a relatively wide temperature range. And the powder flows periodically across the polymer affixed to the mold surface. As a result, the effect of melting is diffused over a relatively wide time frame, with the result being an extended time to fusion. Figure 6.23 clearly illustrates this for time-dependent mold cavity air temperature profiles for crystalline polyethylene and amorphous polyvinyl chloride.[55]

* This experiment demonstrated local hot spots on the mold inner surface, since the black powder fused first to the hotter regions.

** This figure is discussed in detail in the oven cycle time section.

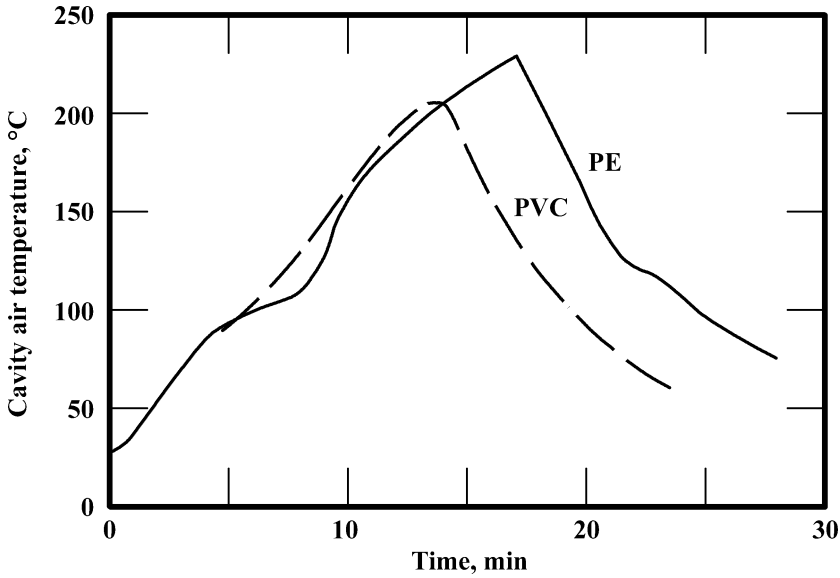

Figure 6.23 Comparison of the heating characteristics of crystalline (PE) and amorphous (PVC) polymers,[55] redrawn

6.15 The Role of Pressure and Vacuum

Commercially, the application of pressure during the densification portion of the process yields parts with fewer, finer bubbles. Technically, pressure acts to increase air solubility in the bulk polymer. Increasing bulk polymer pressure also acts to decrease bubble dimension and internal air pressure in the bubble, which in turn increases the concentration gradient. The overarching effect is one of accelerating bubble extinction. It has also been shown that vacuum or partial vacuum is also beneficial in promoting void-free densification prior to the bubble formation stage.

Note that there are competing effects. Low pressure inside the mold is important as the gas pockets are being formed into bubbles. If vacuum is applied when the bubbles are fully formed, they will get larger. However, the concentration of air in the bulk polymer will drop dramatically, implying that the bubbles should disappear even quicker. A hard vacuum is not required. The vacuum does not need to be applied throughout the heating process. In fact, there is strong evidence that vacuum applied during the early heating stages of the process may be detrimental to uniform powder flow across the mold surface.

6.16 Mathematical Modeling of the Heating Process

It is apparent from the discussion above that the mechanics of powder heating, coalescence, and densification are quite complex and certainly not fully understood. Nevertheless, a general, holistic view of the process is possible. Figure 6.24 is a schematic of the typical heating process.[56] First, it is well known that the mold absorbs substantially more energy than the plastic. As the mold is heating in a nearly constant temperature air environment, its rate of heating is essentially unaffected by the small amounts of thermal heat sink offered either by the sticking, densifying plastic or the air in the mold cavity. As a result, the mold should heat as a lumped parameter first-order response to a step change in temperature, as described above. For all intents, the inside mold surface sees the outside mold surface energy in less than one second. Once the inner mold surface begins to heat, its temperature T_L lags behind the outside mold surface temperature T_W by approximately:*

$$T_L \approx T_W - h(T_{\text{air}} - T_W)L/2K \tag{6.40}$$

The temperature offset is about proportional to the convection heat transfer coefficient and the thickness and thermal properties of the mold material. High oven air flow, thicker molds, and molds of low thermal conductivity act to increase the temperature difference across the mold thickness. The rate of heating of both mold surfaces become equal when the heating time is approximately:

$$\theta_{\text{asymptote}} \approx 0.45L^2/\alpha \tag{6.41}$$

The thermal offset across the mold thickness is shown in schematic as curves A and B in Figure 6.24. For most rotational molding materials, the thermal offset may be only a few degrees at best.**

Consider the case where there is no polymer in the mold cavity. The energy uptake by the air in the cavity depends on convection through a relatively stagnant air layer at the interface between the mold cavity air and the inner mold cavity surface. Thus the air temperature will lag behind that of the inner mold cavity surface. Since the volume of air in a given mold cavity is

* This equation is technically correct for constant heat flux to the surface. The heat flux in rotational molding slowly decreases as the mold temperature increases. For this approximate analysis, it can be considered constant.

** Again, as given in the discussion about Figure 6.1, temperature differences of as much as 30°C have been measured. The anomaly between the predicted and measured temperature differences is not understood.

known, the air temperature can be approximated at any time by solving the transient heat conduction equation with an appropriate adiabatic inner mold cavity surface boundary condition. However, for this heuristic analysis, the time-dependent mold cavity air temperature quickly parallels that of the inner mold cavity surface, as described earlier in this chapter. This is shown as curve *D* in Figure 6.24.

As indicated earlier, the sticking, coalescence, and densification processes are complex interactions of free powder flow and neck formation between irregular particles. Instead of immediately modeling these processes, consider the conditions when all the powder has stuck, melted, and densified. At this time, the polymer is molten and has uniformly coated

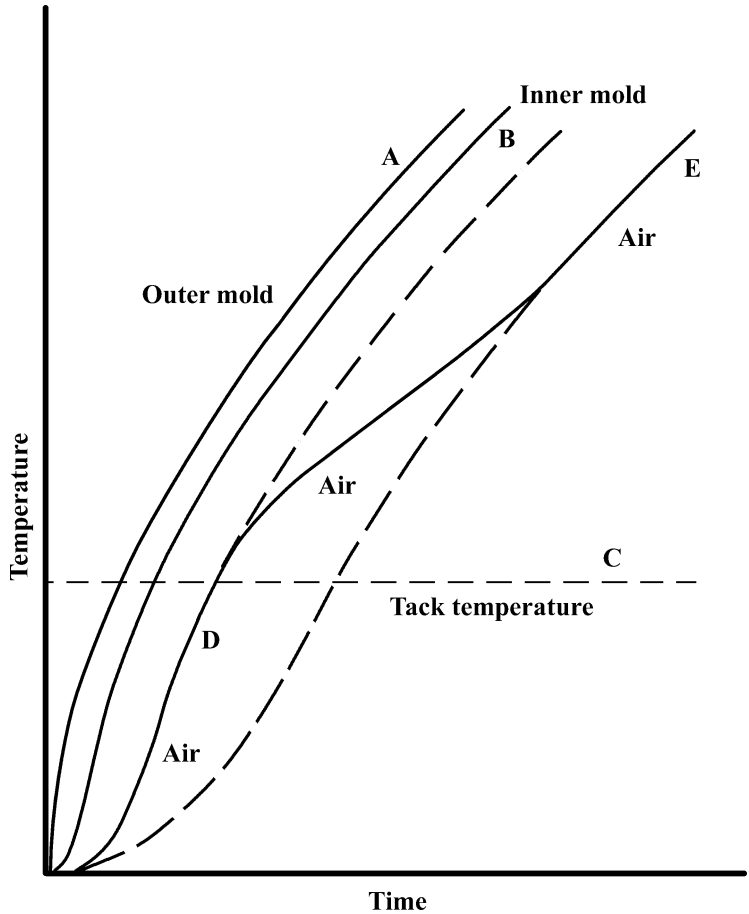

Figure 6.24 Heating temperature profile schematic[56]

the inner mold cavity wall surface. The energy transfer now is through the mold wall, through the liquid polymer layer and into the mold cavity air. The mold cavity air temperature should now be increasing at a rate parallel to the outer mold surface temperature. The offset temperature between the inner liquid polymer surface and the outer mold surface temperature is given approximately by:

$$T_p \approx T_W - [h(T_{\text{air}} - T_W)(L/2K + \Delta/2K_p)] \tag{6.42}$$

where Δ is the thickness of the liquid polymer layer and K_p is the thermal conductivity of the liquid polymer. As is apparent from this approximation, the thicker the polymer layer becomes, the greater the thermal lag becomes. This is seen as a shift away from the original curve *D* in Figure 6.24 to a new curve *E*, the amount of shift being the amount of thermal resistance through the polymer.

As discussed earlier, the transition from curve *D* to curve *E* begins at about the time the inner mold surface reaches the tack temperature of the polymer. The air temperature asymptotically approaches curve E when the entire polymer is densified and molten. This temperature is greater than the melting temperature of the polymer and certainly depends on powder flow, mold geometry, and rate of heating, among other parameters discussed earlier.

This analysis has made some technically inaccurate assumptions. Nevertheless, it illustrates some of the general concepts connected with the rotational mold heating process.

With this overview in mind, now consider mathematical models for the early portion of the heating process. One approach is to consider the powder bed as an infinitely long stationary continuum of known thickness. The appropriate model is the simple one-dimensional transient heat conduction equation, with appropriate boundary conditions:[58] *

$$\rho c_p \frac{\partial T}{\partial \theta} = \frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x} \right) \tag{6.43}$$

* This model was originally proposed as a simpler version of an earlier steady-state circulation model for powder flow.[2] In reality, it represents a model for steady-state slip flow of the powder bed.[57]

where $T(t,0) = T_m(\theta)$ and $dT/dx|_{x=X} = h(T - T_{air})$. Here T_m is the mold temperature and T_{air} is the mold cavity air temperature.

For the simplest version of this model, $\alpha = K/\rho c_p$ is considered constant. Standard graphical solutions for this equation are available when T_m is a known function, such as constant or linear with respect to time.[57] Computer models are easily generated when T_m is more complex or when powder thermal properties are temperature-dependent. As one example, the crystalline heat of melting is accommodated by assuming the powder bed specific heat to be temperature-dependent, or $c_p = c_p(T)$. Densification can be approximated by assuming that the polymer density is also temperature-dependent, or $\rho = \rho(T)$. As a result, this model can be used to approximate the entire heating process, from cold mold insertion into the isothermal oven environment to full densification of the molten polymer. Slip flow of the powder bed comes closest to being characterized by this model.

Recently, a more complex model has been developed. Here the mold is first opened to a flat surface. Then a two-dimensional transient heat conduction equation is applied to a static powder bed of length less than that of the mold.[59] This model allows the mold and any affixed polymer to be mathematically separated from the static powder bed, thus allowing simulation of mold parameters such as contact time length and frequency.

Another approximate energy model has been used when the powder bed appears to circulate in a steady-state fashion.[2] The first assumption is that while a portion of the powder bed is in contact with the mold surface, it is static or nonflowing, and is heated by conduction from the mold surface. The static contact is short-lived, however, as that powder releases from the mold and cascades across the newly-formed static bed. During cascading, the powder particles mix sufficiently well to produce powder of a uniform bulk temperature, which now form a new static bed.*

Energy is transmitted by conduction through the surface of the bed that is in contact with the mold surface. Essentially no energy is transmitted to the bed from the mold cavity air. Since the powder contacts the mold surface for a relatively short time, the powder bed is considered to be infinitely deep relative to the thermal wave entering the bed at the

* The reader should review Figure 6.3 to understand this model.

mold-bed interface.* The appropriate mathematical model is:

$$\frac{\partial T}{\partial \theta} = \alpha_{\text{effective}} \left(\frac{\partial^2 T}{\partial x^2} \right) \tag{6.44}$$

Here x is the distance into the powder bed, assumed to be essentially planar relative to the planar mold surface. $\alpha_{\text{effective}}$ is the thermal diffusivity of the powder bed, as discussed below. The mold surface temperature is given by the exponential equation:

$$T_{\text{mold}} = T_{\infty} (1 - e^{-\beta\theta}) + T^* \tag{6.45}$$

where $\beta = h\alpha/LK$, and T^* is called the offset temperature. If δ is the distance into the powder bed beyond which the effect of the increasing mold temperature is not felt, then the temperature in the powder bed can be approximated by a cubic temperature profile[60] as:

$$T = T_{\text{mold}} \left[1 - (x/\delta)\right]^3 \tag{6.46}$$

The solution to the partial differential equation yields the following expression for δ, the thermal penetration distance:

$$\delta(\theta) = \frac{2\sqrt{6}}{T_{\text{mold}}(\theta)} \left[\int_0^{\theta} \alpha_{\text{effective}} T_{\text{mold}}^2(\theta)\, d\theta \right]^{1/2} \tag{6.47}$$

For a simple step change in surface temperature, the thermal penetration distance is given as:

$$\delta(\theta) = \sqrt{24 \alpha_{\text{effective}} \theta} = 4.9 \sqrt{\alpha_{\text{effective}} \theta} \tag{6.48}$$

This model is valid so long as the dimensionless time is at least:[61]

$$\text{Fo}_{\text{min}} = \alpha\theta/\delta^2 = 0.00756\ \text{Bi}^{-0.3} + 0.02 \quad \text{where} \quad 0.0001 < \text{Bi} < 1000 \tag{6.49}$$

And

$$\text{Bi} = h\delta/K$$

For a linear change in surface temperature, $T_{\text{mold}} = \varepsilon\theta$, the thermal penetration distance is given as:

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* In the discussion that follows, the powder bed is considered to be a continuum with uniform thermophysical properties such as bulk density and thermal diffusivity. If specific bed characteristics are known, the analysis can be modified to include variable thermophysical properties.

$$\delta(\theta) = \sqrt{8\alpha_{\text{effective}}\theta} = 2.83\sqrt{\alpha_{\text{effective}}\theta} \tag{6.50}$$

For linear heating of the mold, the temperature in the powder bed at any time and distance x is then given as:

$$T(\theta, x) = \varepsilon\theta\left[1 - x/\sqrt{8\alpha_{effective}\theta}\right]^3 \tag{6.51}$$

This equation assumes that the mold temperature is increasing linearly rather than exponentially as experimentally determined. Although a closed solution to the thermal penetration distance equation has been obtained for the exponential mold temperature, the linear model has been shown to be quite accurate so long as the static bed contact with the mold surface is restricted to relatively short times.

Keep in mind that the above approximate analysis holds only until the thermal penetration distance value approaches that of the bed thickness. This penetration theory model is coupled with a "mixing cup" step, in which the powder is allowed to achieve uniform temperature before recontacting the mold or mold-affixed powder surface. This yields a time-dependent free powder bed temperature profile. This model is then coupled with a partitioning model, in which the powder at or above tack temperature is allowed to stay with the mold surface, thus depleting the bed.

Recently the circulating bed model has been revisited. Here, the mold is considered to be a sphere with the computational grid centered on the moving powder bed.[62,63] Furthermore, the powder bed is assumed to be well mixed, implying that the speed of rotation of the mold surface is quite high.* A very careful thermal analysis yields nine dimensionless groups, including Biot numbers for heat transfer from the environment to the outer mold surface and heat transfer from the inner mold surface to the rotating powder bed. Three mathematical models are proposed. An analytical solution is obtained by assuming certain thermal effects are negligible. When some of these assumptions are relaxed, a lumped-parameter model is employed, and when many assumptions are removed, a finite difference mathematical model is solved. All three models show that the "mixing cup" temperature of the free powder bed heats very slowly until just before the bed is depleted. This is mirrors well the penetration model analysis given above.

* According to Ref. 62, the mold is assumed to rotate at 10–20 RPM.

Heating characteristics of a powder bed behaving in avalanche flow, being a hybrid between the steady-state models of slip flow and full circulation, are best analyzed using the penetration model.

6.17 Total Oven Cycle Time

As noted, there are three distinct segments to the oven cycle time. The first is the time needed to get the mold to the tack temperature. Since the polymer powder is in contact with only a portion of the mold during this time, this time should be nearly independent of the final part wall thickness. The second is the time needed to coalesce and densify the polymer against the mold surface. And the third is the time needed to ensure that the polymer is fully fluid and all bubbles have collapsed.[65] An overall heat balance reveals some interesting aspects about rotational molding. Consider first the amount of energy required to heat the mold assembly from room temperature to a temperature a few degrees below the oven set point temperature, T_{final}. If the mold mass is m_m and the mold has a heat capacity of $c_{p,m}$, the amount of energy required is:

$$Q_{\text{mold}} = m_m\, c_{p,m}\, (T_{\text{final}} - T_0) \tag{6.52}$$

The amount of energy needed to heat the powder charged to the mold from room temperature to its final fluid temperature, $T_{\text{polymer, final}}$, is obtained from Figure 6.9,[64] as:

$$Q_{\text{polymer}} = m_{\text{polymer}}\, \Delta h_{\text{polymer}} \tag{6.53}$$

Example 6.1

MDPE spheres with 6 mm thick walls are rotationally molded in a 600-mm diameter spherical mold of 10-mm thick aluminum. Calculate the energy needed if the mold is heated to 275°C and the plastic is heated to an average of 220°C. The mold and aluminum both start at 20°C. The density of the MDPE is 945 kg/m^3.

Solution

The volume of the aluminum mold is:

$$V_m = 4\pi R^2 d_m = 4\pi(0.3)^2(0.01) = 0.011 \text{ m}^3$$

The physical and thermal properties of aluminum are obtained from Table 5.1. The mass of the mold is given as:

$$M_m = \rho_m V_m = 2800(0.011) = 31.7 \text{ kg}$$

The energy uptake by the aluminum mold is:

$$Q_m = M_m C_{p,m}(T_{\text{oven}} - T_0) = 317 \times 917 \times 255 = 7.4 \text{ MJ}$$

The volume of MDPE is:

$$V_p = 4\pi R^2 d_p = 4\pi\,(0.3)^2\,(0.006) = 0.0068 \text{ m}^3$$

The density of MDPE is 945 kg/m^3 and so the mass of plastic is:

$$M_p = \rho_p V_m = 945\ (0.0068) = 6.4 \text{ kg}$$

From Figure 6.9, the enthalpy to heat MDPE from 20°C to 220°C is 150 kcal/kg or 0.628 MJ/kg. The energy uptake by the HDPE is therefore given as:

$$Q_p = M_p(Dh_p) = 6.4 \times 0.628 = 4.02 \text{ MJ}$$

The Q_m/Q_p ratio is 1.84:1. It has been shown many times that the Q_m/Q_p ratio is usually greater than 1:1 and can be as much as 30:1, depending on the extent of support pillars, externally mounted air directing fins, and other heat sinks. In other words, it takes far more energy to raise the mold to a fixed temperature than to heat the polymer tumbling inside the mold.

Example 6.2

For the mold in the previous Example, calculate how long it takes the inside surface of the mold to reach a tack temperature of 100°C. The mold starts at 20°C and the heat transfer coefficient for the mold when it is in an oven at 300°C is 48 W/m^2 K.

Solution

The time to reach tack temperature is obtained directly from:

$$\frac{T_\infty - T_{\text{tack}}}{T_\infty - T_0} = e^{-\frac{h\alpha\theta}{Kd_m}}$$

Replacing α with $K / \rho c_p$ yields:

$$\theta = -\frac{\rho c_p d_m}{h} \ln\left(\frac{T_\infty - T_{\text{tack}}}{T_\infty - T_0}\right)$$

Using the data in Table 5.1 for aluminum, and substituting the data given, the time to reach the tack temperature of 100°C is 3 minutes.

The times to reach this tack temperature for other oven temperatures, relative to an isothermal oven temperature of 300°C are given in Table 6.6. It is apparent that the time to tack temperature decreases with increasing oven temperature and increases with increasing tack temperature. For instance, if it takes 5 minutes to reach a tack temperature of 100°C with an oven temperature of 300°C, it will take about 4 minutes (5 × 0.82) to reach that temperature with an oven temperature of 325°C. And if it takes 5 minutes to reach a tack temperature of 100°C with an oven temperature of 300°C, it will take 7 minutes (1.4 × 5) to reach a tack temperature of 125°C.

Table 6.6 Relative Times to Reach Two Tack Temperatures at Different Oven Temperatures

T_{oven} (°C)	Relative Time to Reach a Tack Temperature of 100°C	Relative Time to Reach a Tack Temperature of 125°C
275	1.12	1.58
300	**1.0**	1.40
325	0.9	1.25
350	0.82	1.14
375	0.76	1.04
400	0.7	0.96

Experimentally, it is seen that the time at which the kink temperature* occurs is dependent on the amount of powder charged to the mold. It is also apparent that the rate at which the mold cavity air temperature increases is also dependent on the amount of powder charged to the mold, indicating energy interchange between the mold cavity air and the powder during the early heating stage. Although there may be some slowing of the mold temperature rate of heating as

* The kink temperature was described earlier as a strong indication that polymer is adhering to the mold surface. There is a strong indication that the polymer tack temperature and the measured kink temperature coincide for a given polymer.

the amount of powder charged to the mold is increased, the relative effect should be quite small.

Conduction is the primary mode of energy transmission through a static substance, whether it is powder, coalesced network structure, or polymer melt. As noted earlier, the penetration model predicts that the energy impulse from the mold should be detected at the free surface of the polymer in proportion to:

$$x \propto \sqrt{\alpha\theta} \tag{6.55}$$

If L is the thickness of the polymer layer contacting the mold, then the time for the free surface of the polymer to reach a given temperature, say the melt temperature, should be proportional to the square of the thickness:

$$\theta \propto L^2 \tag{6.56}$$

This is confirmed from conventional transient conduction where the Fourier number is considered to be the defining expression:

$$\text{Fo} = \alpha\theta / L^2 \tag{6.57}$$

where α is the thermal diffusivity, and L is the thickness of the polymer, in any state. It can be shown that the Fourier number represents the dimensionless time at which the free surface of the polymer structure reaches a specific temperature, say, the polymer melt temperature. This is written symbolically as:

$$\frac{T_{\text{mold}} - T_{\text{melt}}}{T_{\text{mold}} - T_0} = g\left(\frac{T_{\text{oven}} - T_{\text{melt}}}{T_{\text{oven}} - T_0}\right) = f\left(\frac{\alpha\theta}{L^2}\right) \tag{6.58}$$

Note that the inner mold temperature is exponentially temperature-dependent, but considered to be essentially independent of the layer of polymer adhering to it. As a result, the time to reach the polymer melt temperature should be given approximately as:

$$\theta \propto L^2/\alpha \tag{6.59}$$

In other words, theory says that the time to reach the melt temperature at the free surface of the densifying powder bed increases in proportion to the square of the increase in powder charge weight to the mold. Note that even though the thermal diffusivity for the polymer changes throughout the coalescence and densifying phases, the *relative* effect remains the same. Therefore,

doubling the charge should increase the time to achieve full densification by a factor of four.

Analysis of experimental mold cavity air temperature measurements indicates that this theory overestimates the effect of thickness. Table 6.7 shows experimental data for the time taken for the mold internal air temperature to reach the kink temperature. These data are for a particular rotational molding machine. As a result, the absolute time values will be different for different machines. The times to heat an empty mold to the kink temperature are also included for reference. It can be seen that even in a relatively small mold, it takes between 4 and 5 minutes to heat an empty mold to the tack temperature.

Table 6.7 Measured Values for Time to Kink Temperature in a 221-mm Diameter Spherical Mold

Part Wall Thickness	**Time to Reach Kink Temperature at Oven Temperature of**		
(mm)	**280°C (min)**	**300°C (min)**	**350°C (min)**
0	5	4.5	4
3	7.25	6.1	5
6	9.8	8	6

It is interesting to observe the relative changes in time to reach the kink temperature as a function of wall thickness and oven temperature, as shown in Table 6.7. Rather than a squared power relationship between time and part wall thickness, as predicted by Fourier's law, the experimental data suggests a power-law relationship:

$$\theta_k \propto L^m \tag{6.60}$$

Where θ_k is the time to the kink temperature. In this case the constant m is close to 0.75.

Furthermore, it appears that the mold cavity internal air temperature reaches a value that is approximately equal to the plastic melt temperature in a time that is proportional to the square root of the wall thickness. Extending this approach further, it is observed that the time for the mold cavity internal air to reach any temperature in excess of these temperatures can be described by a power-law relationship to part wall thickness:

$$\theta_\alpha \propto L^{n'} \tag{6.61}$$

where n' may have a different value than the value of m in equation (6.60).

The total oven cycle time may be written as:

$$\theta_{oven} = \theta_{(room \rightarrow kink)} + \theta_{(kink \rightarrow melt)} + \theta_{(melt \rightarrow exit)} \tag{6.62}$$

From the above discussion, it can be written that:

$$\theta_{oven} = \theta_{(thickness,\, L_1)} \left(\frac{L_2}{L_1} \right)^n \tag{6.63}$$

where n is not necessarily equal to m or n' of earlier equations. Experimental data show that for any particular machine and mold combination, the value of n can vary from 0.5 to 2. This is because there are many interacting variables. It is probably not reasonable to expect that there is one universal relationship that links part wall thickness to oven time for all types of heating conditions. Figure 6.25 shows some experimental data for typical oven times as functions of part wall thickness for different molds and machines. The line represents the square law, but with an offset. It is thought that the offset represents the time required to heat and cool an empty mold.

The oven set temperature will also have an effect on oven times, as illustrated in Table 6.8 for the 221-mm sphere mold described earlier.

Table 6.8 Measured Values for Oven Times in a 221-mm Diameter Spherical Mold

Part Wall Thickness	**Oven Time for Oven Temperature of**		
(mm)	**280°C (min)**	**300°C (min)**	**250°C (min)**
0	14	11	8.5
3	21	18.3	13.8
6	29.3	26	20

If the overall oven cycle time is known at one exit temperature, say T_1, it can be found at another, say T_2, from:

$$\frac{\theta_1}{\theta_2} = \ln \left(\frac{T_\infty - T_1}{T_\infty - T_2} \right) \tag{6.64}$$

Similarly, if the overall oven cycle time is known at one set oven temperature,

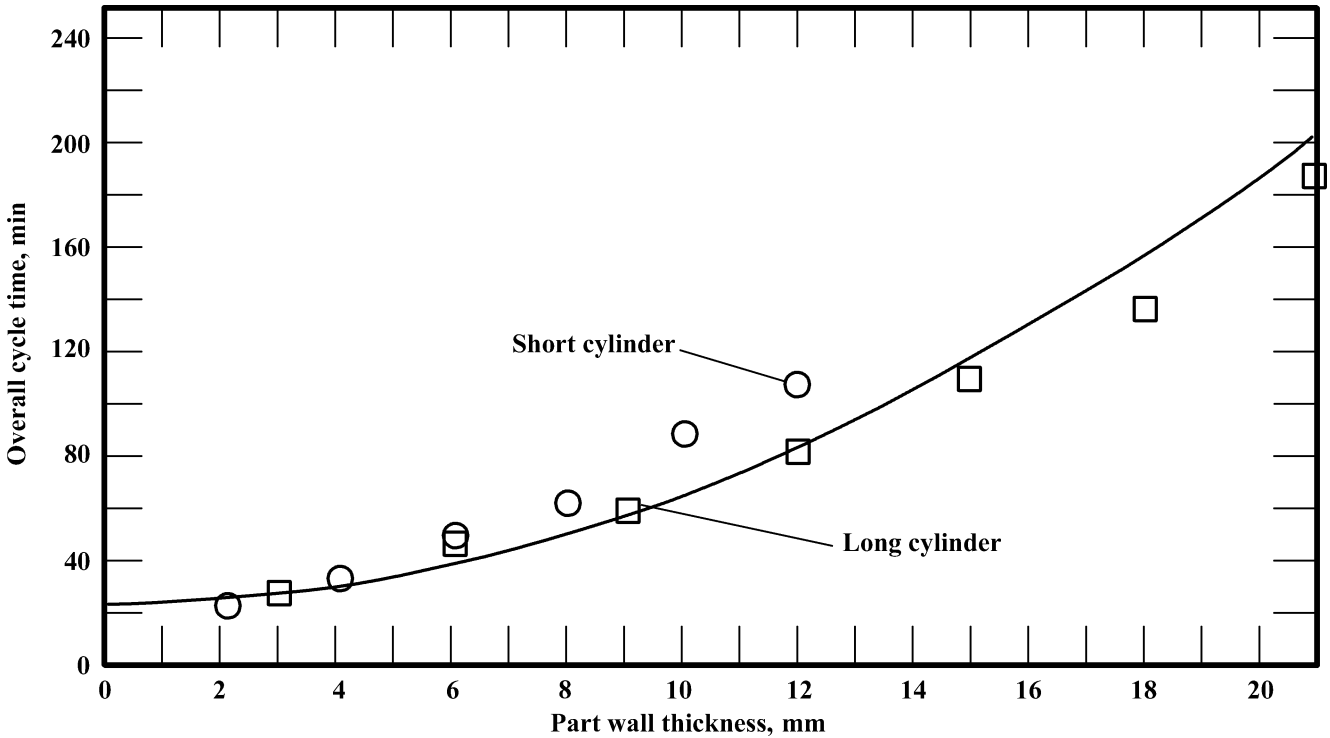

Figure 6.25 Comparison of experimental overall oven cycle times for two mold configurations with empirical power-law, time = 25 + 0.4(part thickness)^2

say, $T_{\infty 1}$, the overall oven cycle time can be found at another, say, $T_{\infty 2}$, from:

$$\frac{\theta_1}{\theta_2} = \ln\left(\frac{(T_{\infty 2} - T_{\text{exit}})/(T_{\infty 2} - T_0)}{(T_{\infty 1} - T_{\text{exit}})/(T_{\infty 1} - T_0)}\right) \tag{6.65}$$

As is apparent, oven cycle time is a function of many factors, including:

- Isothermal oven temperature
- Mold composition
- Mold thickness
- Heat transfer coefficient inside the oven
- Enthalpy of the polymer between room temperature and the desired exit temperature from the oven
- Ultimate thickness of molten polymer against the mold surface
- Relative bulk density of the powder (which affects the thermal diffusivity)
- Desired exit temperature of the polymer

Table 6.9 Actual Heating Cycle Times for Aluminum Mold

Polymer	Oven Temperature (°C)	Thickness (mm)	Exit Temperature (°C)	Time (min)
HDPE	300	2	210	13
HDPE	300	4	210	23
HDPE	300	6	210	32
HDPE	300	8	205	43
HDPE	300	10	210	56
MDPE	275	6	210	22
PP	325(?)	3	240	18
PC	375(?)	3	265	22
PVC	200(?)	5	133	23
ABS	350(?)	3	300	17
ETFE	325	4.5	290	26
Hytrel	300(?)	3	220	13.5
Nylon 6	325(?)	3	230	16
XLPE	260	3	180	13.5
PFA	330	3	300	33

Because there is no universal theory that is accurate enough to predict oven cycle time, at least one time must be determined for a given polymer in a given mold at a known temperature. Having that database, there are then two ways of determining oven cycle time as a function of part wall thickness. The more detailed method uses information about kink and densification temperatures. The simpler method simply assumes that the oven cycle time is proportional to the part wall thickness to the 1.5-power. Some typical heating cycle times are given in Table 6.9.

6.18 Cooling and the Optimum Time for Removal from Oven

Technically, the ideal time for part removal from the oven is immediately after the polymer is fully densified into a monolithic liquid film uniformly coating the mold surface, and long before there is evidence of oxidative or thermal degradation, either manifested as color change on the interior of the liquid film or as loss in mechanical properties of the demolded part. Until very recently, the determination of this ideal time relied on many years of experience and many trials. Now, the extensive use of portable multiplexed thermocouple platforms and computer simulation of the process are providing the processor with ways of predicting the ideal times.

This section concentrates on cooling the monolithic liquid polymer layer into a solid, rigid part. First, it must be emphasized that it is far easier to cool the mold and its contents to room temperature than it is to initially heat the assemblage to its desired fusion temperature. Cooling can be accomplished simply by directing flooding water onto the hot mold. While this bold action will cool the mold and its contents in a fraction of the time it takes to heat the assemblage, it will result in undesirable polymer morphology. It may also lead to badly distorted parts. And in certain instances, it may actually collapse the part and even the mold. In other words, although it is possible to rapidly quench the mold and its contents, it is almost never desired, practical, or practiced. The reasons for this are detailed below.

6.19 Some Comments on Heat Transfer During Cooling

In rotational molding, as with other plastics processing methods, it is useful to be able to predict the changes in temperature that occur with time. Once again, a detailed analysis of such situations can be complex. However, simplified methods give perfectly acceptable results, if we are only

interested in temperature changes at one point in the polymer, at the surface for example, or at the center line.

One such simplified method is based on two dimensionless parameters. The Fourier number, Fo, is written, as before, as:

$$\text{Fo} = \alpha\theta/d^2 \tag{6.66}$$

where θ is time, d is the full thickness of the plastic if it is being heated or cooled from one side,* and α is the thermal diffusivity of the plastic melt. The value for α is obtained from standard handbooks on plastics and is generally about 1×10^{-7} m^2/s for most plastics.

The other dimensionless number is the temperature ratio or reduced temperature, ΔT:

$$\Delta T = \frac{(T_\theta - T_i)}{(T_m - T_i)} \tag{6.67}$$

where T_θ is the temperature at time θ, T_m is the temperature of the mold, and T_i is the initial temperature of the plastic. These two dimensionless groups are very useful because there is a unique relationship between them that depends only on the geometry of the surface that is gaining or losing heat. Figure 6.26 shows this relationship for a flat sheet. A flat sheet approximates most rotationally molded parts, since part wall thickness is usually small when compared to other part dimensions. These dimensionless numbers are used in the following example.

Example 6.3

A rotationally molded plastic part is 8 mm thick. During molding, the plastic is heated to a uniform temperature of 200°C. Then in the cooling bay, the mold temperature is quickly lowered to 20°C. Determine how long it will take the internal surface of the plastic to cool to 90°C. What is the midplane temperature of the plastic at this time?

---

* Even though heat transfer is taking place from the inside of the polymer layer to the inner mold cavity air, it is considered sufficiently small as to be ignored in simple analyses such as this. In this way, cooling of the polymer melt in rotational molding is quite similar to the cooling of the polymer melt against the blow mold wall and the cooling of the stretched polymer sheet against the thermoform mold wall. Note that if the plastic is heated or cooled from both sides, as with injection molding, d is the half-thickness of the plastic.

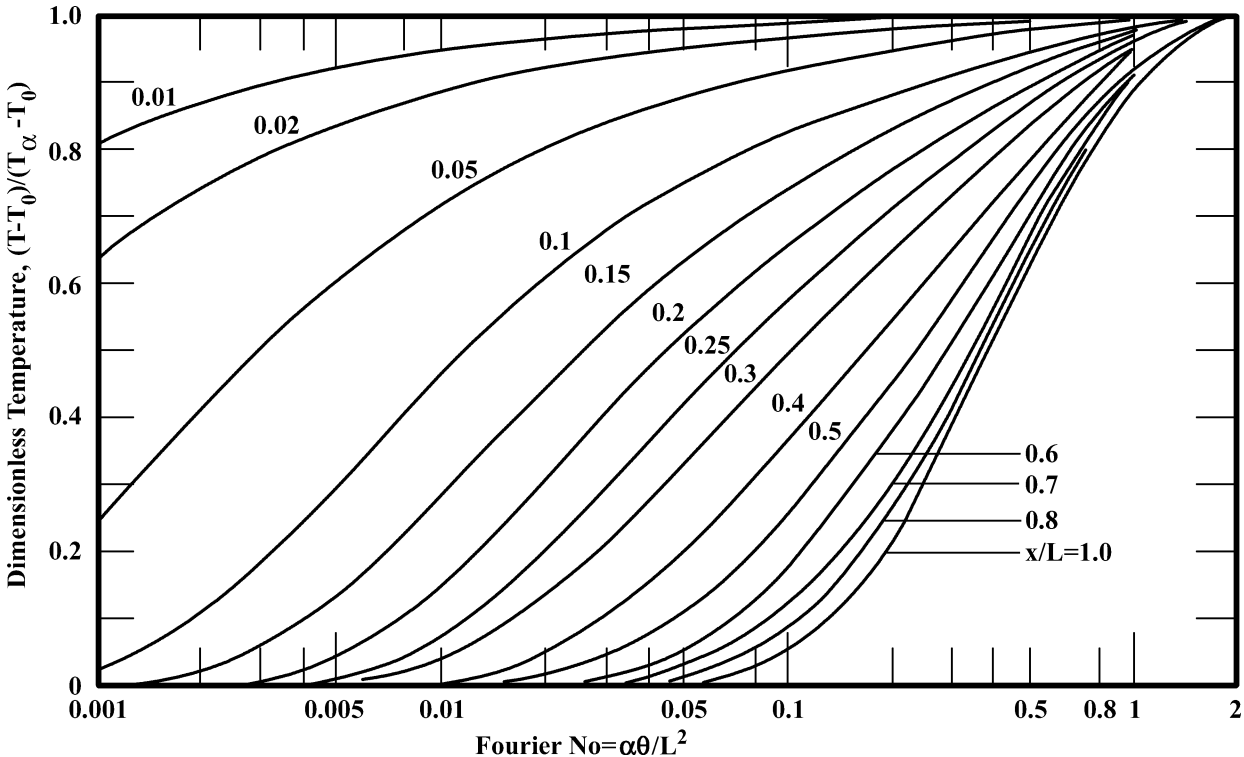

Figure 6.26 Transient heat conduction through slab,[61] redrawn, with courtesy of McGraw-Hill Book Company, New York

Solution

The temperature ratio, ΔT, is given as:

$$\Delta T = \frac{(T_\theta - T_i)}{(T_m - T_i)} = \frac{90 - 200}{20 - 200} = 0.611$$

The Fourier number from Figure 6.26 is given as Fo = 0.48. The cooling time is then given as:

$$\text{Fo} = 0.48 = \alpha\theta/d^2 = (1 \times 10^{-7})\,\theta/(8 \times 10^{-3})^2$$

Or the cooling time is 307 seconds or 5 minutes 7 seconds. From this figure, the midplane temperature is determined, from x/d = 0.5 at Fo = 0.48, as ΔT = 0.728, or T_{CL} = 69°C.

6.20 Thermal Profile Inversion

As noted above, the primary source of energy to heat the polymer powder to a monolithic liquid film is forced hot air. Energy is conducted through the metal mold wall into the powder, which coalesces and densifies against it. As a result, the outer mold surface temperature is hottest and the air inside the mold cavity the coolest at the time of exit from the oven is as shown in Figure 6.27. The magnitude of the thermal gradient across the polymer liquid film depends on the rate of energy input at the outer mold surface, the thermal properties of the mold and its thickness, and the thermal properties of the liquid polymer and its thickness. The air in the mold cavity can be considered stagnant and therefore acts primarily as an insulation blanket to the inner surface of the liquid layer. The approximate thermal lag through the polymer was given above as:

$$T_p \approx T_W - [h\,(T_{\text{air}} - T_W)(L/2K + d/2K_p] \tag{6.68}$$

where T_p is the approximate free surface temperature of the polymer of thickness d, T_W is the outer mold surface temperature, h is the convective heat transfer coefficient of the air in the oven, $T_{\text{oven air}}$ is the isothermal oven air temperature, L is the mold thickness, K is its thermal conductivity, and K_p is the thermal conductivity of the liquid polymer.*

* Note that it can be shown mathematically that the true temperature profile through the liquid layer is nonlinear. This approximate model assumes that the temperature profile is linear through the liquid layer.

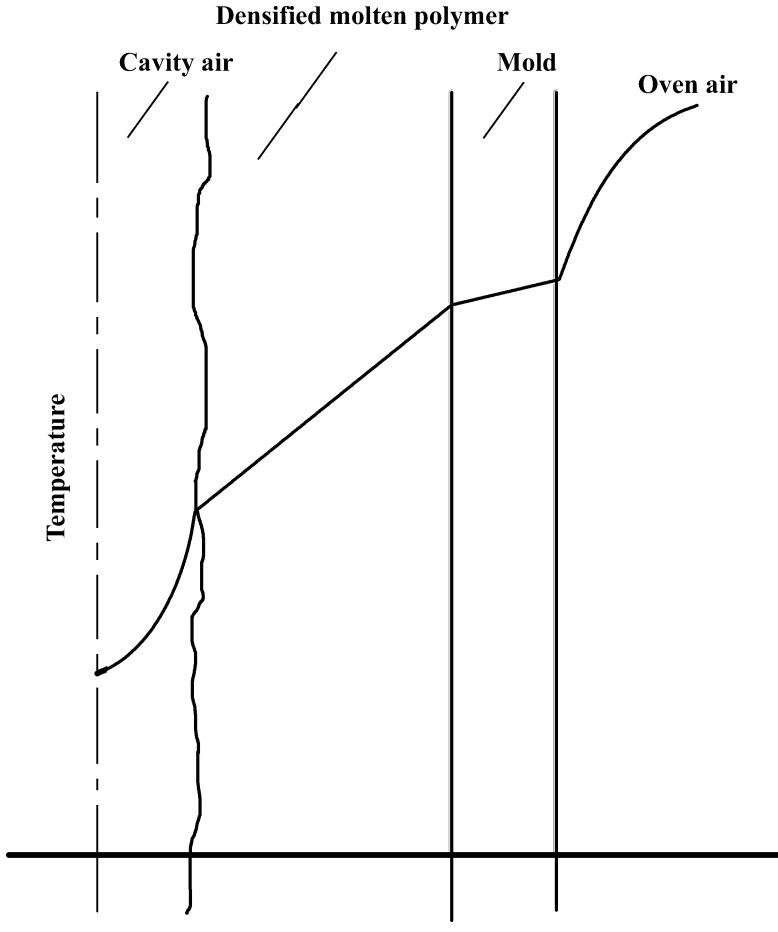

Figure 6.27 Temperature profile through mold and molten polymer at exit from oven

Immediately upon exiting the oven or primary energy source, the mold surface temperature begins to fall. In other words, energy is now being transferred from the hotter mold surface to the surrounding cooler environment. At some time during the cooling process, the temperature profile will be maximum somewhere in the liquid layer (Figure 6.28). The exact time depends on the relative thermal properties and thicknesses of the mold and the liquid polymer. The maximum temperature value moves inward as a function of time, initially from the outside mold surface to finally at the inside polymer-air interface. Typically, thermal inversion occurs within minutes of the exit of the mold assembly from the oven. The rate at which this inversion occurs will

depend on the rate at which energy is removed through the outer mold surface, as well as the relative thermal properties and thicknesses of the mold and polymer.

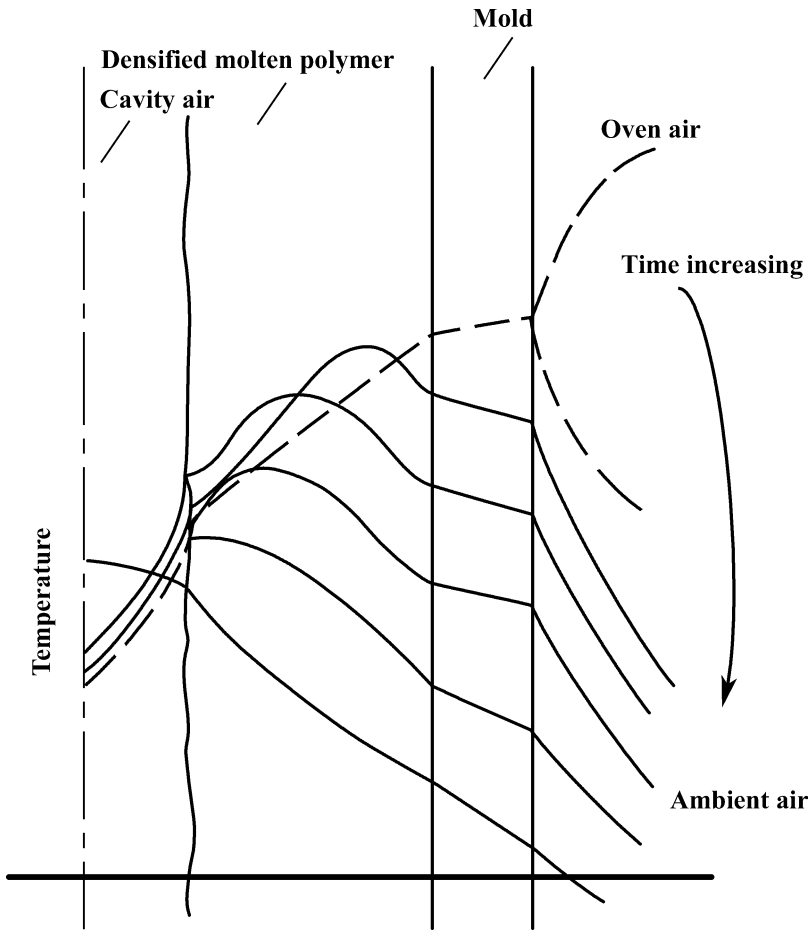

Figure 6.28 Time-dependent temperature profile through mold and polymer during thermal inversion

The arithmetic that governs this portion of the cooling cycle is similar to that for the heating portion, with the exception that the thickness of the polymer layer is fixed and independent of the local temperature. The general equation for conduction through the polymer is:

$$\rho_p c_{p,p} \frac{\partial T}{\partial \theta} = K_p \frac{\partial^2 T}{\partial x^2} \tag{6.69}$$

where K_p, the thermal conductivity of the polymer, is assumed to be independent of temperature or position. There are two ways of considering conduction through the mold wall. The general equation for conduction through the metal is:

$$\rho_m c_{p,m} \frac{\partial T}{\partial \theta} = K_m \frac{\partial^2 T}{\partial x^2} \tag{6.70}$$

There are two boundary conditions at the interface between the polymer and metal:

$$T(L_m, \theta) \equiv T(0_p, \theta) \text{ and } K_m \left.\frac{\partial T}{\partial x}\right|_{x=L_m} = K_p \left.\frac{\partial T}{\partial x}\right|_{x=0_p} \tag{6.71}$$

The first states that the temperatures in the polymer and the metal are equal at the interface, and the second states that the heat flux from the metal equals that from the polymer. The boundary condition at the interface between the liquid polymer and the inner cavity air is:

$$-K_p \left.\frac{\partial T}{\partial x}\right|_{x=L_p} = h_a \left[T_a - T(L_p, \theta)\right] \tag{6.72}$$

where T_a is the inner cavity air temperature and h_a is the convection heat transfer coefficient inside the mold cavity. Similarly, the boundary condition at the interface between the outer mold surface and the environmental fluid coolant is given as:

$$-K_m \left.\frac{\partial T}{\partial x}\right|_{x=0} = h_e \left[T_e - T(0, \theta)\right] \tag{6.73}$$

where h_e is environmental fluid convection heat transfer coefficient and T_e is its temperature. The remaining boundary condition is the temperature conditions at time $\theta = 0$:

$$T(x_p,0) = T(x_p) \text{ and } T(x_m,0) = T(x_m) \tag{6.74}$$

where $T(x_p)$ and $T(x_m)$ are obtained by solving the heating equation to the time where the mold assembly is rotated from the oven.* Note that these equations

* Note that unlike the equation used to describe mold heating, this equation assumes a thermal gradient through the mold wall. The assumption that the mold assembly can be thermally represented simply by an empty mold is justified during the early stages of heating, where the powder is in intimate contact with the mold for only a short time. This assumption seems valid at least until the mold temperature reaches the tack temperature of the powder. For cooling, the polymer represents a heat source that must be coupled with the conduction of energy through the mold wall. The coupling boundary conditions are best solved when both equations are of the same type, or distributed parameter equations.

are traditional transient one-dimensional heat conduction equations, coupled only through the interfacial boundary conditions. They are solved either by finite difference* (FDE) or finite element** (FEA) methods.

The second way is to consider that the thermal transfer through the metal is so efficient that the lumped parameter equation can be used here in the same way it was used to describe mold heating, that is:

$$L\rho_m c_{p,m} \frac{\partial T}{\partial \theta} = h_e \left(T_e - T\right) \tag{6.75}$$

where h_e is the environmental convection heat transfer coefficient outside the mold and T_e is the environmental temperature. The solution for this equation, assuming that T_e is constant (which it may not be in practical cooling situations), is:

$$\frac{\left[T_{\text{exit}} - T_{\text{mold}}\right]}{\left[T_{\text{exit}} - T_0\right]} = 1 - e^{(h_e \alpha / LK)\theta} \tag{6.76}$$

where T_{mold} is the mold temperature, T_{exit} is the mold temperature when the mold exits the oven at $\theta = 0$, and T_0 is the environmental temperature. The temperature profile through the polymer can then be given by the linear equation cited earlier, written as:

$$T_p(x,\theta = 0) \;=\; T_{\text{exit}} - \left[h\,(T_{\text{oven}} - T_{\text{exit}})\,(L/2K + x/2K_p)\right] \tag{6.72}$$

Now only one equation, the distributed parameter transient heat conduction equation through the polymer, needs to be solved, with the appropriate boundary conditions given by the time-dependent mold surface temperature and the convection boundary condition to the mold cavity air.

6.21 Cooling and Recrystallization

Polyolefins are semicrystalline polymers. The crystallization level of a particular semicrystalline polymer depends to a great degree on its molecular structure, as shown in Table 6.10.

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* Although there are many FDE books, Dusinberre[66] addresses this heat transfer problem directly. Unfortunately, it is out-of-print and probably available only through technical libraries.

** Although it appears that for this simple problem that FDE is entirely satisfactory, FEA has been used extensively recently for solving transient one-dimensional heat conduction problems. Ref. 67 is a good basic source of information.

Table 6.10 Degree of Crystallinity of Semicrystalline Polymers

Polymer	Density Range (kg/m^3)	Crystallinity (%)
Polypropylene	920–940	45–55
LDPE	910–925	45–65
LLDPE	918–920	35–45
MDPE	925–940	65–75
HDPE	940–965	75–90
PA-12 (nylon 12)	1020	10–25
PA-6 (nylon 6)	1130	40–50
PA-66 (nylon 66)	1140	50–60*
PET	1130–1450	0–40*

* Upper values achieved by slow cooling, annealing

As these polymers cool from their molten state, they recrystallize. Certain polymer characteristics, such as impact strength, are strongly influenced by the rate at which they are cooled while crystallizing. Crystallites form around nucleants such as low molecular weight plasticizers, inorganics such as catalyst particles and talc, contaminants and ordered regions in the melt, such as highly oriented fringed micellular structures. Typically, in rotational molding, the crystallites grow in a spherical manner, outward from the nucleant in a network of twisted lamellae.[68] The rate at which a polymer recrystallizes depends on the type of polymer. Table 6.11 shows typical recrystallization rates for polymers at temperatures 30°C below their reported melting temperatures.[69] It is apparent that the crystallization rates of polyethylenes are many times greater than those of, say, nylon 6 or polypropylene.

What this means in rotational molding is that once the temperature profile in polyethylene has been inverted, the mold can be relatively rapidly cooled without appreciably affecting the crystalline morphology or crystalline order of the polymer.* The common practice for rotational molding PE, then, is to cool the mold to room temperature using a fog, mist, water spray,** or just room air (Figure 6.2).

* Of course, keep in mind that the internal air pressure should remain at atmospheric. If the vent is insufficient in cross-sectional area or if it is plugged, rapid quenching of the mold can cause a vacuum inside the mold and the mold can collapse.

** Currently, independent multiarm machines allow for two and even three cooling stations. As a result, many production facilities are opting for waterless cooling. This is discussed in detail in a later section of this chapter.

Table 6.11 Recrystallization Rates for Several Polymers at Temperatures 30°C Below Their Reported Melting Temperatures[69]

Polymer	Crystallization Rate (μm/min)
Polyethylene	5000
Nylon 66 (PA-66)	1200
Polyoxymethylene (POM)	400
Nylon 6 (PA-6)	150
Polytrifluorochloroethylene (PTFCE)	30
Polypropylene	20
Polyethylene Terephthalate (PET)	10
Polystyrene	0.25
Polyvinyl Chloride	0.01

Water quenching of slowly crystallizing polymers such as nylon 6 and PP is not recommended. Simply put, a slowly crystallizing polymer may not achieve an equilibrium level of crystallinity during the cooling step. Although the part made by rapid cooling *may* look dimensionally stable when newly formed, the polymer molecular structure may reside in a metastable state. Over a long time, polymer chains may move molecularly in an effort to achieve a more stable state. This is particularly true if the polymer has a sizeable portion of amorphous or noncrystalline structure and is used above its glass transition temperature. This molecular motion is manifested as warping and distortion. Figure 6.29 illustrates this effect of cooling in terms of the enthalpy of a typical crystalline polymer.[70] In Figure 6.30 are photomicrographs showing the effect of cooling rate on spherulitic size for polypropylene.[71] Figure 6.31 shows heating and cooling DSC curves for several rotationally molded crystalline polymers. The classic case is polypropylene homopolymer, which crystallizes at a rate less than 1% of that of PE, and is typically about 45% crystalline and has a glass transition temperature of about 0°C.

Differential Scanning Calorimetry or DSC is an analytical technique that yields important information about the melting and recrystallization temperatures of polymers when subjected to various heating rates. The left portion of Figure 6.32 is a DSC heating rate for PP at a heating rate of 16°C/min or about 25°F/min. A melting temperature of about 164°C is found. Subsequently, the PP is cooled from the melt at the same rate,* the

* Note that if a rotational mold is cooled from 250°C, say, to 25°C, say, in 14 minutes, the average cooling rate is about 16°C/min.

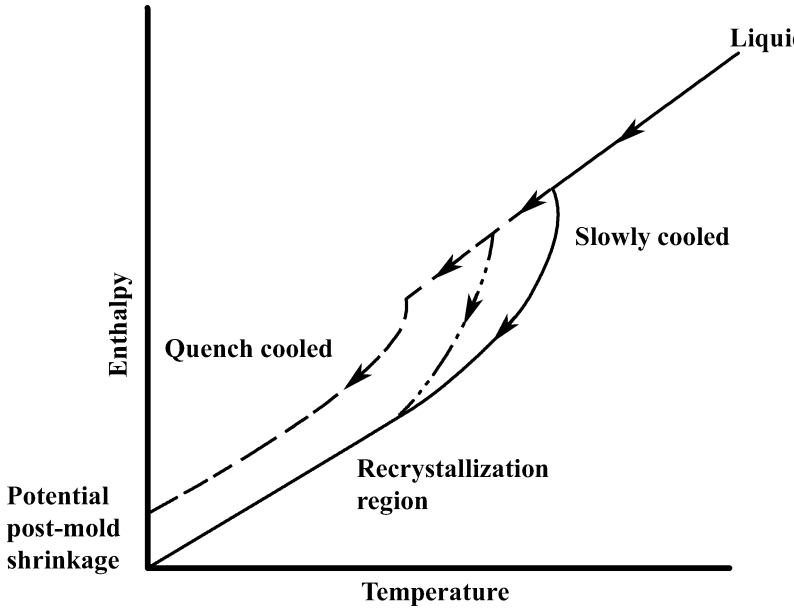

Figure 6.29 Effect of cooling rate on specific volume of a crystallizing polymer, redrawn, with permission of Hanser Publishers, Munich (Note the specific volume offset that may lead to long-term dimensional change)

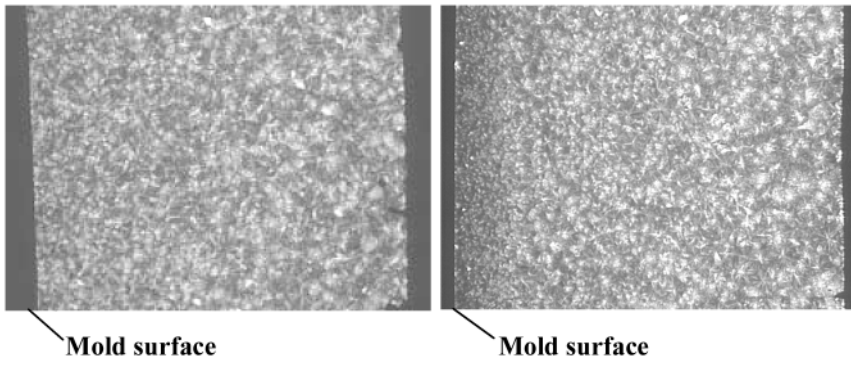

Figure 6.30 Photomicrographs of effect of cooling on spherulitic size on PP. Left: Air cooling. Right: Water cooling

right portion of Figure 6.32, and shows a recrystallization temperature of 103°C,[72] or a phase change temperature difference of more than 60°C. Changes in cooling rate also affect the morphological or crystalline structure of PP, as seen in Table 6.12.[73]

Table 6.12 Morphological Effects of Cooling on Polypropylene from the Melt[73]

Effect of decreased cooling rate
Increased degree of crystallinity
Increased level of crystalline perfection
Increased lamellar thickness
Increased spherulitic size
Increase in b-spherulites (mp 147°C)
Increased elastic modulus
Increased yield strength
Increased molecular diffusion
Increased level of segregation of uncrystallizable impurities at intercrystalline boundaries
Increased weakness of intercrystalline boundaries
Decreased tie chain density
Decreased ductility on deformation
Fewer lamellae interconnections
Higher stress concentrations at surfaces of crystallites
Reduction in room temperature tensile strength
Dramatic reduction in elongation at break
Transition from ductile to brittle fracture
Reduction in total impact energy to break
Effect of orientation
Increased number of taut-tie molecules
Increased stress relaxation shrinkage
Increased level of tie chain density
Increased strain-induced crystallinity
Increased room temperature elastic modulus
Slight increase in yield strength
Unbalancing of biaxial elongation at break
Decreased, unbalanced impact strength

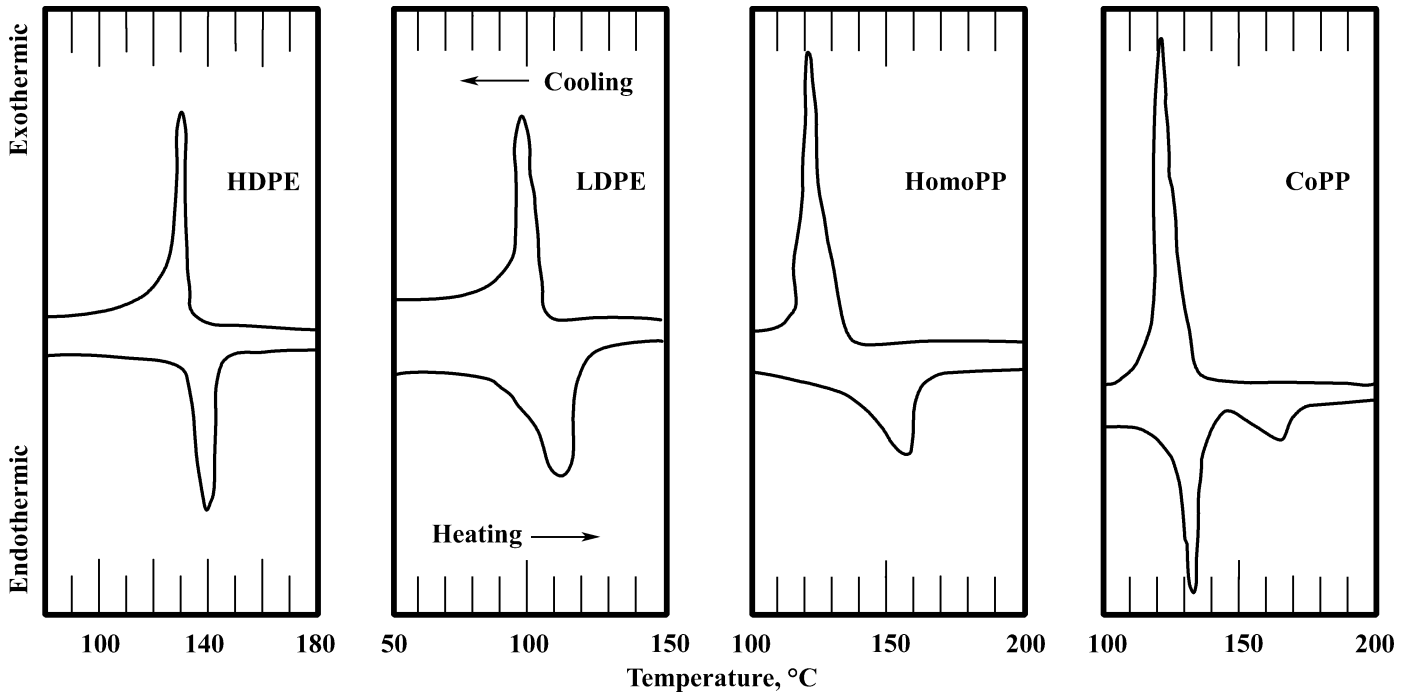

Figure 6.31 Heating (left/right) and cooling (right/left) DSC curves for crystallizing polyolefins,[70] redrawn, with courtesy of John Wiley & Sons, New York

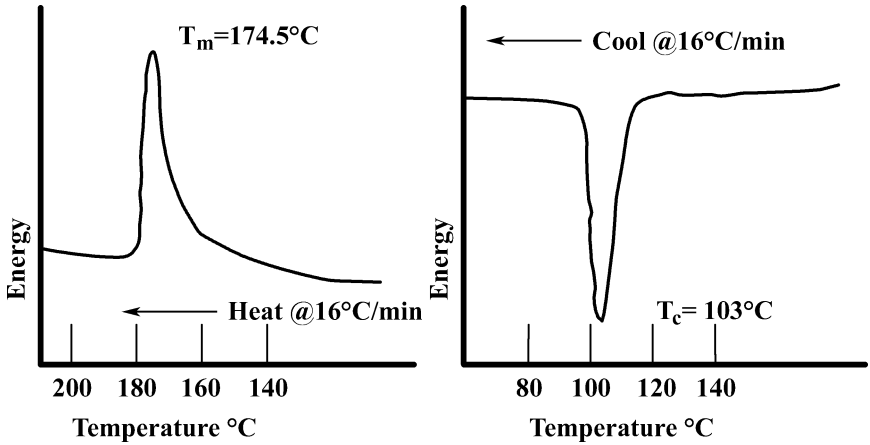

Figure 6.32 Comparison of DSC heating (left) and cooling (right) traces for homopolymer polypropylene,[72] redrawn, with courtesy of John Wiley & Sons, New York

Further, small amounts of crystallization nucleant such as sorbitol alter the recrystallization temperature and recrystallization rate (Table 6.13).

Table 6.13 Adduct Effect on Polypropylene Recrystallization Temperature

	Recrystallization Temperature
Copolymer	
No Clarifier	92°C
Dibenzylidene Sorbitol (DBS)	105°C @ 1800 ppm
Methyl Dibenzylidene Sorbitol (MDBS)	107°C @ 1200 ppm
Millad 3988 (Unknown Chemistry)	108°C @ 600 ppm
Homopolymer	
No Clarifier	102°C
Dibenzylidene Sorbitol (DBS)	115°C @ 1800 ppm
Methyl Dibenzylidene Sorbitol (MDBS)	120°C @ 1800 ppm
Millad 3988 (Unknown Chemistry)	121°C @ 1200 ppm

In other words, much longer air cooling times are needed for slowly crystallizing polymers such as PP and nylons than for polyethylenes. And since the cavity air remains hotter longer, oxidation of the inner layer of the formed part is expected to be more severe. And further, since polypropylene and nylon are both slow crystallizers and quite thermally sensitive, great care is needed to ensure that the polymers do not degrade during the cooling step.

It should be noted parenthetically, however, that very rapid quenching of polyethylene could be either beneficial or detrimental. Slow cooling allows spherulites to grow quite large, while quenching results in many, very small spherulites. Table 6.14 compares the relative effect of cooling rate on the characteristic properties of polyethylene.

Table 6.14 Effect of Increased Cooling Rate on Polyethylene Properties

Property	**Effect**
Spherulite Size	Reduced
Modulus	Decreased
Elongation at Break	Increased
Impact Strength	Increased
Yield Strength	Increased
Brittleness Temperature	Increased
Light Transmission	Increased

Information on the modeling of the cooling portion of the rotational molding process was given in the earlier section. For materials that experience very abrupt transitions such as freezing, over very narrow temperature ranges, the mathematical model describing cooling through the liquid undergoing freezing is inadequate as presented. It must be replaced with two coupled models, one describing cooling through the liquid and another describing cooling though the solid. In addition, the location of the liquid-solid interface must be carefully defined to include latent heat of fusion. However, for polymers, the liquid-to-solid transition takes place over a typically large temperature range. As a result, the traditional freezing model just described is not needed. Nevertheless, recently, the coupled model has been solved, with apparently good agreement with experimental data[74,75] (Figure 6.33).

In a simpler approach, the two thermal properties most influenced by crystallization, density and specific heat, ρ and c_p, respectively, are simply allowed to be highly temperature-dependent throughout the freezing region. This allows a single equation to model the entire cooling process of the polymer from its liquid state to room temperature. More importantly, if the density and specific heat are only temperature dependent and not time dependent, they can be removed from the left-side transient differential without compromising the arithmetic form of the transient one-dimensional heat conduction equation* or the

* Note that this assumption may not always be correct, particularly if the polymer is a slowly crystallizing one and if the mold assembly is undergoing quenching.

traditional finite difference model used to solve the equation. Thus the heat conduction equation for the polymer becomes:

$$\rho(T)\, c_p(T)\frac{\partial T}{\partial \theta} = K\frac{\partial^2 T}{\partial x^2} \tag{6.77}$$

Note here that this equation assumes that the thermal conductivity is independent of temperature.

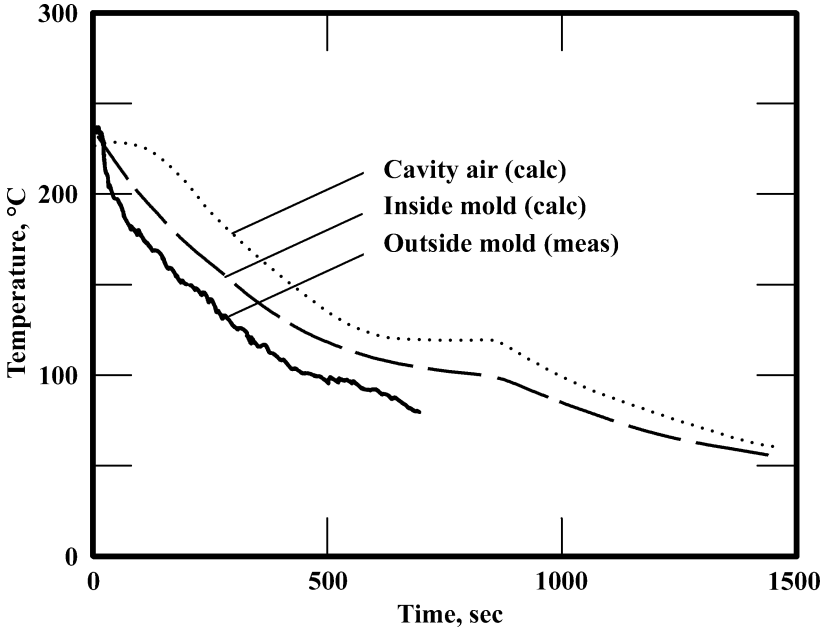

Figure 6.33 Comparison of experimental and theoretical cooling curves[74,75]

6.22 Air Cooling — Heat Removal Rate

As detailed earlier during the discussion of heat transfer in the convection oven, air is a poor heat transfer medium. The convection heat transfer coefficient, *h*, is a measure of the resistance to heat transfer across a thin near-stagnant fluid layer between the bulk of the fluid and the solid surface. Table 4.2 gives approximate values for the heat transfer coefficient for several fluids that might be used to cool the mold and its molten contents. As the bulk fluid motion increases, the value of *h* decreases, meaning that the resistance to heat transfer decreases. Therefore, air moved with fans is about two to three

times more efficient in removing heat than is quiescent air. Similarly, heat removal is increased another two to three times when high velocity blowers are employed instead of fans.

In practice, fans are usually employed at two times during the cooling process. For polyethylenes, once the temperature profile through the polymer has inverted, so that the liquid surface against the inner mold wall is cooler than the liquid surface in contact with the cavity air, fans are used to hasten the cooling, through the recrystallization portion of the cooling process. Fans are also used for nylons and polypropylene where part walls are relatively thin. Once recrystallization is complete, cooling rates are usually increased using either a mixture of air and water mist or a misting fog. Technically, this method of cooling can continue until the mold reaches room temperature. Practically, however, when the mold temperature is not much lower than 160°F or 65°C, water spray is stopped and the air circulating fans are used to blow the evaporating water vapor from the mold surface. This allows the mold to be reasonably moisture-free when it is presented to the attendants at the demolding station.

6.23 Water Cooling — Heat Removal Rate

As is apparent in Table 4.2, water is an efficient coolant, with heat transfer coefficients more than ten times larger than values for the most efficient air cooling techniques. Because of this, water cooling must be used judiciously. It should be employed only after thermal inversion and recrystallization are completed and only if it is certain that there is adequate air passage between the inner cavity air and the outside atmosphere.*

The internal cavity air should be pressurized prior to water cooling, particularly if the mold assemblage is to be drenched with water. It has been demonstrated elsewhere[76] that if, during cooling, the part pulls away from the mold surface even a slight amount, the effectiveness of heat removal is dramatically decreased. This is discussed in detail later in this chapter.

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* Improper venting can lead to partial vacuum in the cavity. This partial vacuum can suck the still-soft polymer from the mold wall surface. This is particularly serious with large flat surfaces. If an air layer is formed at some point along the mold wall surface, heat transfer from the part in that area will be reduced, the part will stay warmer there than in surrounding areas, resulting in localized warping and inconsistent polymer morphology. For thin sheet-metal molds, the partial vacuum can distort the mold walls. If the vacuum is great enough, the mold may buckle or collapse.

6.24 Pressurization

From the beginning, it has been known that uncontrolled internal or mold cavity pressure can cause serious damage to both plastic parts and metal molds. As a result, molds have always been equipped with some form of passive venting, usually an easily removed section of pipe stuffed with a piece of spun glass or glass wool. In addition, thermal oxidation of the inner surface of the molded part has been passively controlled for decades by adding small bits of "dry ice" or solid carbon dioxide to the polymer powder just before the mold is clamped closed. Newer machines are now equipped with hollow double arms, thus allowing positive mold cavity pressure control. As discussed earlier, application of a partial vacuum aids in air removal and porosity reduction during the coalescence and densification steps.

Application of slight positive pressure during cooling is beneficial in holding the soft polymer part against the inner mold wall throughout the recrystallization portion of the cooling cycle and even as the part is cooling to demolding temperature. Internal cavity pressures are typically 15 to 35 kPa (2 to 5 lb/in^2) above atmospheric. However, the mold maker must be warned if internal cavity pressure is to be used with a specific mold, so that he/she can construct the mold capable of withstanding not just this modest pressure differential but accidental overpressure of, say, an additional 150%. The role of pressurization to minimize shrinkage during cooling is discussed below.

Although positive cavity pressure control requires modern machinery and more expensive molds (because of the extra plumbing needed), product quality benefits and the fear of a plugged vent causing mold collapse is minimized if not obviated. It has also been shown that cycle times can be reduced significantly and impact properties improved.

6.25 Part Removal*

The rotational molding process ends when the cooled mold assembly is rotated to the load/unload station. Typically, part removal is an almost-mirror image of powder loading. Opening sequence depends on the number of molds. Obviously, if there is only one mold on the arm, after the mold is opened by removing clamps, the arm can be rotated to allow the part to be dropped or easily pulled from the mold. For very complicated

* The design of parts for easy removal from molds is detailed elsewhere.[77]

stacked molds or multipart molds mounted on spiders attached to both sides of the arm, the unloading sequence must be carefully orchestrated to obtain minimum "mold open" time. For multipart molds, where mold sections are completely removed from the supporting mold frame, a very ritualistic protocol must be established to minimize damage to these sections and to ensure proper and efficient reassembly sequence. As noted in the mold design chapter, although features such as power assisted clamps, mechanical hinges, and pry points that are built directly into the mold certainly add to the initial mold cost, they pay for themselves in reduced unloading and loading times. Recently, one mold maker* has designed a turn-screw wheel closure for family molds that allows all molds to be closed and clamped, and of course opened at one time.

6.26 Effect of Wall Thickness on Cooling Cycle Time

As noted in the heating section, oven cycle time increases with increasing final part wall thickness. Conduction is the primary mechanism for powder heating and coalescence, melting and heating the polymer melt, then cooling and recrystallizing the polymer against the mold wall. As noted earlier in this chapter, the Fourier number is the operative dimensionless group describing the interrelationship between polymer thermal properties, wall thickness, and time:

$$\mathrm{Fo} = \alpha_{\text{effective}}\theta/d^2 \tag{6.78}$$

where $\alpha_{\text{effective}}$ is the effective thermal diffusivity,** d is the instant thickness of the polymer against the mold surface and θ is the running time. The Fourier number for both the oven cycle time and the cooling cycle time should remain constant in order to achieve the same degree of fusion and thermal history on the polymer. Increasing the weight of the powder charge increases the bulk powder thickness, the polymer melt thickness, and the recrystallized polymer thickness. To maintain a constant value for the Fourier number, both the oven cycle time and the cooling cycle time must increase in proportion to the square of the increase in polymer thickness.

* Wheeler-Boyce Co., Stow, Ohio.

** Note in conduction that the thermal properties of multiphase powder, melting, melt heating and cooling, and recrystallization can all be treated as *effective* thermal diffusivities.

6.27 Overview and Summary of Thermal Aspects of the Rotational Molding Process

Other than the initial stages of the process, where powder is free to move across the mold surface and the coalescing powder bed, the rotational molding process is characterized as a nonshear, low-pressure transient heat transfer process. Since polymers have very low thermal properties, optimization of the process focuses on understanding convection of fluids to the mold and conduction of energy to and through the polymer mass. Powder particle coalescence and densification, air dissolution, and recrystallization are important but nevertheless secondary aspects of the process.

6.28 Introduction to Liquid Rotational Molding

Liquid rotational molding has an extensive lifeline. Slip casting of clay pottery is depicted on Egyptian tomb walls and Minoan amphorae. In slip casting, a slurry of clay and water is poured into a porous mold, usually made of plaster. As the mold is rotated, the slurry coats the mold wall, and water is absorbed into the plaster, thereby drying the slurry closest to the wall. After some time, the mold is emptied of the excess slurry. The clay coating the mold is then allowed to dry, the mold is opened and the dried clay shape, called "greenware" is removed. It is then fired in an oven until it vitrifies into a monolithic structure. Liquid rotational molding follows the slip casting concept in two ways. In slush molding, common with PVC plastisol for the manufacture of open-ended hollow parts such as gardening boots, an excess of liquid is poured into the mold perhaps filling it to the top. The mold is then immersed in a heated bath, where gelation of the PVC plastisol begins at the mold surface.* When the gelation has continued for a predetermined time, the mold is up-ended and the ungelled PVC plastisol is poured out. Closed molds in slush molding can also be rotated in a manner similar to the techniques used in rotational molding. The gelled coating on the mold surface is then heated to fuse the PVC, as described below.[78] Liquid rotational molding, using equipment similar to that used for powder rotational molding, produces closed parts beginning with an exact charge of liquid. This section focuses on this form of liquid processing.

6.29 Liquid Polymers

Liquid systems require a different technical approach than the powder rotational molding described above. First, it must be understood that there are

* PVC plastisol gelation was discussed in Chapter 2.

many types of liquid systems, most of which, such as epoxies and unsaturated polyester resin, are thermosetting resins. PVC plastisol and nylon 6 are the primary exceptions. Chapter 2 detailed the characteristics of these liquid polymers.

6.30 Liquid Rotational Molding Process

Many aspects of rotationally molding liquids are different from rotational molding of powders. Probably the most significant is the interaction between the rate of heating and the rate of reaction. Figure 6.34 shows the time-dependent viscosities for polycaprolactam, PVC plastisol, and polyurethane resins for typical rotational molding conditions.[79] It is apparent that at some point in the process, the viscosity of the liquid quickly increases to a level where it is no longer flowable. Many studies have been made on the various aspects of liquids contained in rotating vessels.[80–89] Figure 6.35[90] shows the four characteristic flow stages or phases of liquid rotational molding. A fifth stage, hydrocyst formation, is a secondary flow effect that is discussed separately.

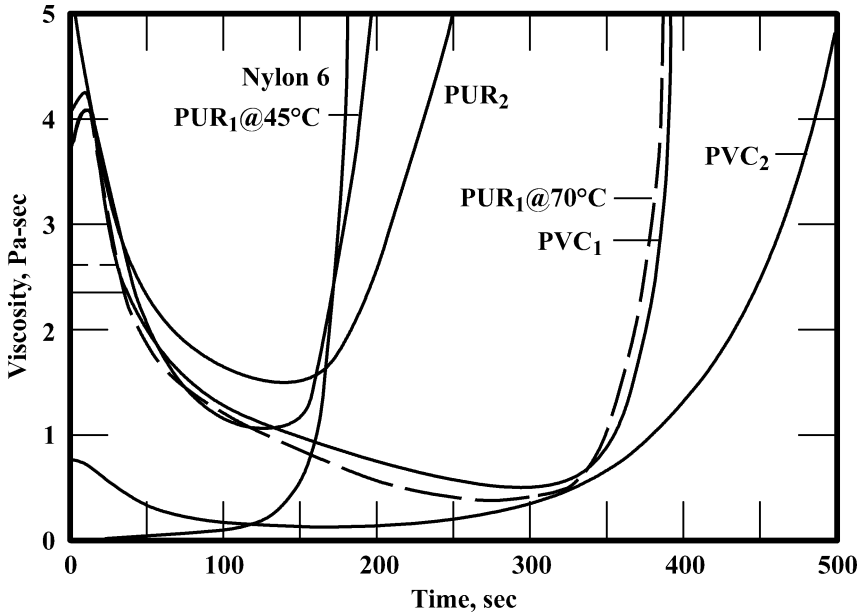

Figure 6.34 Time-dependent viscosities for various liquid rotationally moldable resins,[79] redrawn, with courtesy of the Queen's University, Belfast

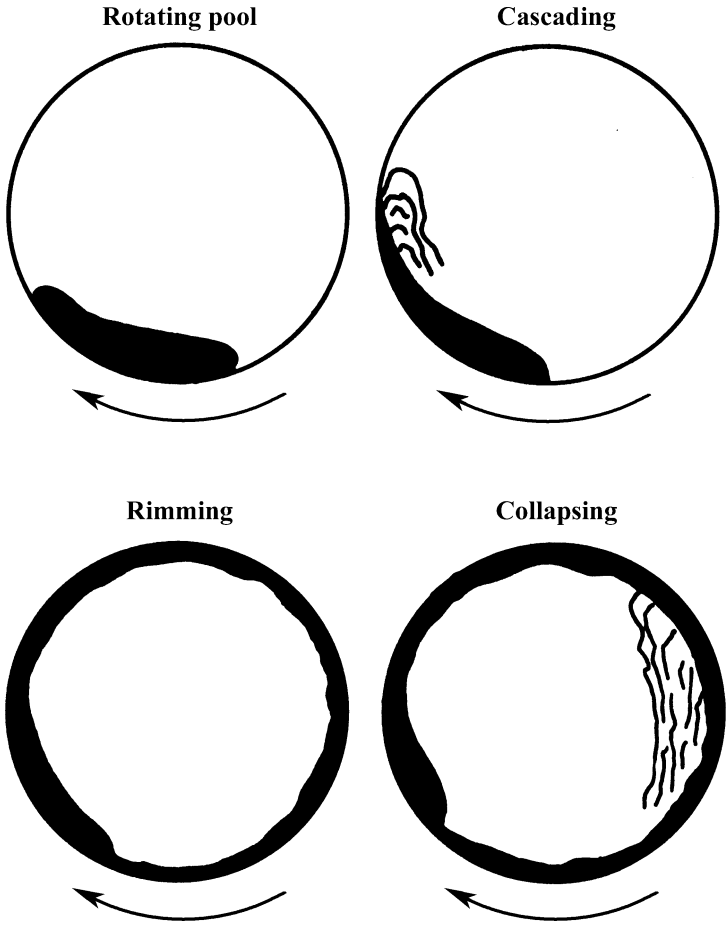

Figure 6.35 Four stages of liquid response to rotating flow.[90] Solid body rotation not shown

6.30.1 *Liquid Circulating Pool*

At low rotational molding speeds and/or low liquid viscosity, the majority of the liquid remains in a pool in the bottom of the mold in a fashion similar to that for the powder pool. The liquid pool rotates, unlike the typical powder pool. Since liquid has much greater thermal conductivity than powder, the liquid temperature is quite uniform throughout the pool. Some liquid is drawn onto the mold wall, however. As expected, the liquid layer thickness is determined by gravitational drainage and the viscosity and speed of withdrawal of the

mold wall from the pool. A first approximation of the average thickness, t_{avg}, of the liquid layer is given as:

$$t_{avg} = a\,(\mu V/\rho g)^{1/2} \tag{6.79}$$

where μ is Newtonian viscosity, V is speed of withdrawal, usually given as $R\omega$ where R is the mean radius of the mold and ω is the speed of rotation, ρ is the density of the liquid and g is gravitational acceleration.

6.30.2 *Cascading Flow*

As the mold speed increases and/or the liquid viscosity increases, the liquid layer begins to thicken. The liquid is carried over the top, then cascades or flows down the opposite side of the inside of the mold. Cascading flow is usually an intermediate flow phenomenon.[91] However, it is sometimes seen as "fingers" on the inside of a formed part, particularly with PVC plastisol.

6.30.3 *Rimming Flow*

As the mold speed and/or viscosity further increases, the liquid layer is taken up and over the top and is returned to the pool with essentially no dripping or draining.[92,93] The thickness of the now steady-state liquid layer is given typically by:

$$t/R = (3\mu\omega/\rho g R)^{1/2} \tag{6.80}$$

The symbols are the same as in eq. (6.79). This does not imply, however, that the pool has been completely depleted.

6.30.4 *Solid Body Rotation*

In solid body rotation, or SBR, the mold speed and/or the polymer viscosity is so high that there is no liquid flow.[94] It is imperative that all the liquid originally in the pool now reside on the mold wall. Otherwise, the liquid left in the pool will begin to form cylinders or balls, which will begin to wipe the liquid off the mold wall. One model for SBR gives the following relationship:

$$t/R > C(\omega\mu/\rho g R)^{1/2} \tag{6.81}$$

Another relationship, for reactive polyester resins is:

$$\omega = C(t\rho g/R\mu)^{2/3} \tag{6.82}$$

6.30.5 *Hydrocyst Formation*

A secondary flow effect, known as a hydrocyst, occurs primarily in horizontal rotating cylinders (Figure 6.36).[95,96] The rotating forces cause ridges to form at regular intervals at a right angle to the axis of the cylinder. As viscosity increases, the ridges consolidate into ribs, which then become webs or membranes that may completely close off the cylinder.* Hydrocysts form about when:

$$\mathrm{Fr} = \mathrm{Re} \tag{6.83}$$

where $\mathrm{Fr} = \rho\omega^2/g$, the Froude number, and $\mathrm{Re} = t^2\rho\omega/\mu$, the Reynolds number.

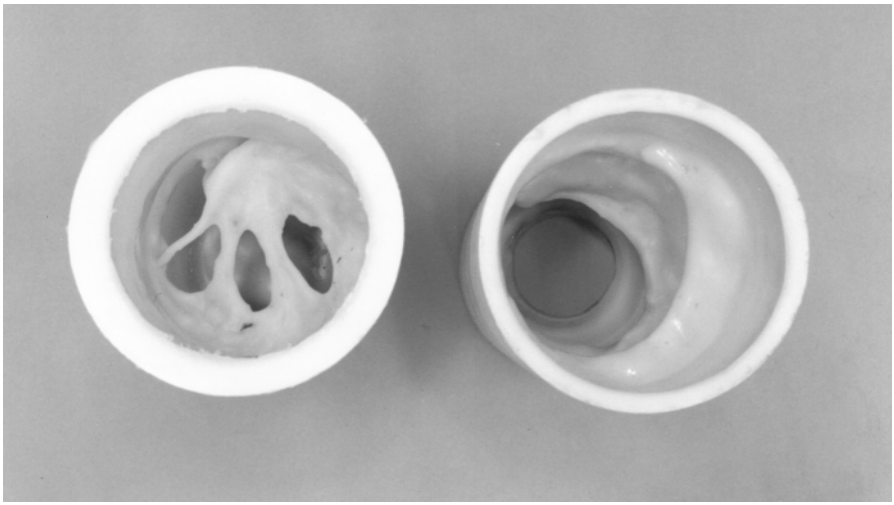

Figure 6.36 Examples of hydrocysts in reactive polycaprolactam,[95,96] courtesy of the Queen's University, Belfast

This is rearranged to read:**

$$t = (\mu\omega/g)^{1/2} \tag{6.84}$$

Not only do hydrocysts deplete plastic from the walls of the part, they dramatically alter the mechanical performance of the part. The interrelationship between these flow phenomena is seen for catalyzed unsaturated polyester resin in Figure 6.37.[97] The Froude number, being the ratio of

* The hydrocyst is not a flow instability. It is a stable flow effect, with repeatable spacing and rib characteristics.

** E.M.A. Harkin-Jones correctly points out that this expression contains no mold dimension.

drag force of the wall to gravitational forces causing drainage, is shown as a function of Reynolds number, being the ratio of inertial force to viscous force. As the resin viscosity increases, the Reynolds number decreases, other factors remaining constant. Thus the forming process begins at relatively high Reynolds number and constant Froude number and progresses essentially horizontally from the pooling region, through cascading, rimming, stable hydrocyst formation, and eventually to solid body rotation. At least for the case shown, hydrocyst formation is inevitable. It is imperative, therefore, that the resin mass be moved carefully through this region, without gelation. Otherwise, hydrocysts will remain in the final part. An example of frozen-in hydrocysts in horizontally rotated polycaprolactam cylinder is shown in Figure 6.38.[98] *

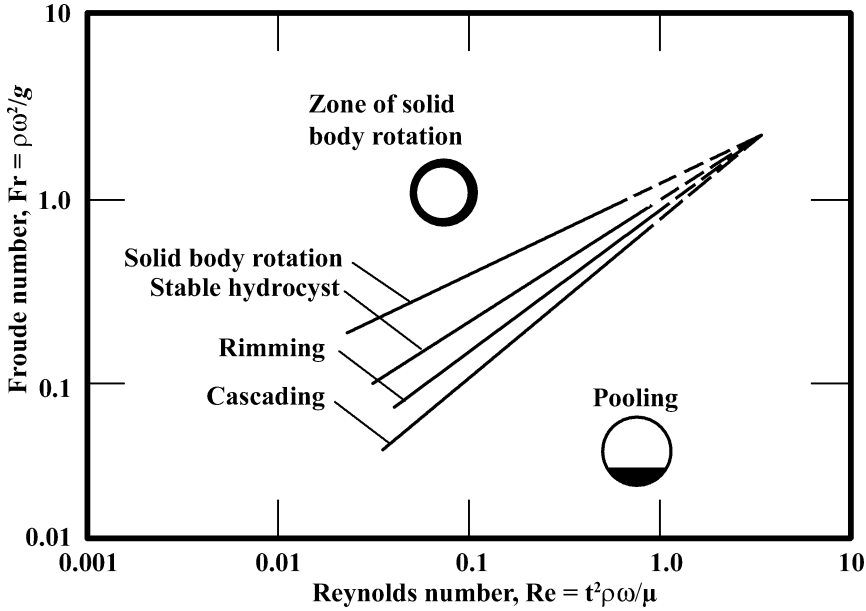

Figure 6.37 Various fluid flow phenomena observed for unsaturated polyester resin,[97] redrawn, with permission of copyright holder

* There is evidence that hydrocyst formation occurs chiefly when the mold is preferentially rotated on a single axis. In one experiment with unsaturated polyester resin, stable hydrocysts, formed during single-axis rotation of a horizontal cylinder, quickly combined and then collapsed when the cylinder was rotated in a traditional rock-and-roll fashion.

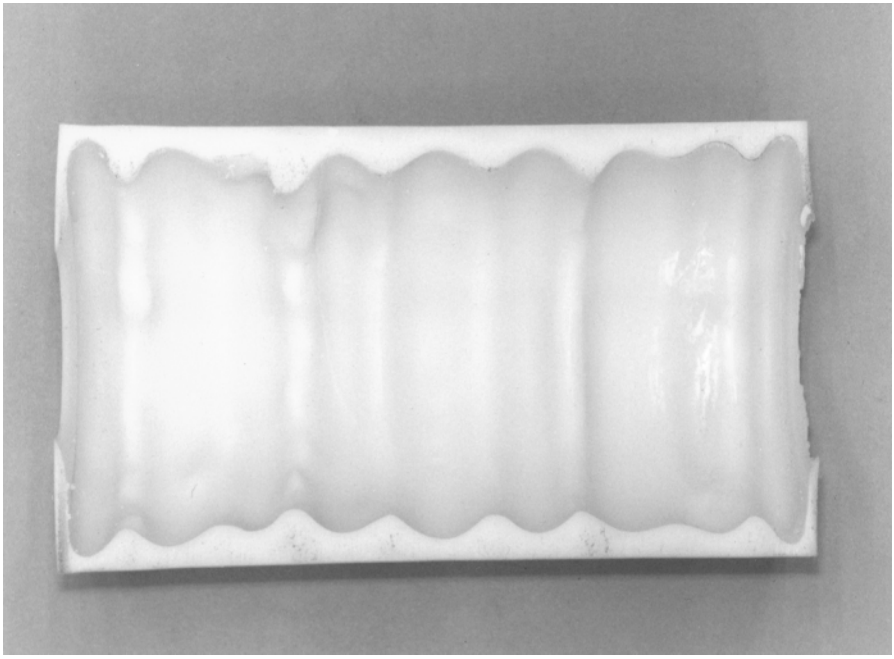

Figure 6.38 Frozen-in hydrocysts in polycaprolactam,[98] courtesy of the Queen's University, Belfast

6.30.6 *Bubble Entrainment*

Most technical liquid rotational molding studies have been done on regular or simple molds, such as cylinders, spheres, and cubes. Most practical applications usually include nonregular shapes. Early in the rotational molding process, when the liquid viscosity is very low, liquid temporarily trapped on a projection or overhang may release from the body of the liquid and may drip onto liquid below. This dripping is sometimes referred to as "drooling" or in severe cases, "glopping."

When liquid drips, air may be entrapped between the free liquid and that on the wall. The entrapped air may quickly form into spherical bubbles. Although some bubble dissolution may occur into the polymer, the increasing polymer viscosity may quickly stabilize small bubbles. As with bubbles entrapped in powdered polymers during coalescence, a few bubbles may not result in reduced physical properties in the part. However, large bubbles and many bubbles can result in points of stress concentration and subsequent reduction in stiffness and impact strength.

6.30.7 *Localized Pooling*

It is well-known in powder rotational molding that outside corners of parts are thicker than sidewalls and inside corners are thinner. For powder, this is directly attributed to the accessibility of the mold corner to the heating medium. Outside corners are more accessible and get hotter quicker than do inside corners.[99] For basically the same reason, sharper outside corners yield thicker part corners and sharper inside corners yield thinner part corners. In liquid rotational molding, the local tangential velocity dictates the part corner thickness. The further the mold corner is from the center axes of the co-rotating arms, the greater the tangential velocity becomes. This is seen from the following relationship:

$$V \text{ (ft/min or cm/sec)} = R\omega \tag{6.85}$$

where ω is the rate of rotation of the mold and R is the distance of the corner from the center of the arm axes. As seen in the simple flat plate withdrawal equation, the thickness of the liquid adhering to the plate is proportional to the square root of the velocity:

$$t_{avg} \propto V^{1/2} \tag{6.86}$$

Typically this effect is manifested as thicker corners on portions of parts that are farthest from the mold axes. This effect is sometimes called "localized pooling." Further, since both powders and liquids must flow into and out of the corner, large radiused corners are desired.

6.31 Process Controls for Liquid Rotational Molding

The critical aspect of liquid rotational molding is the polymer time- and temperature-dependent viscosity. Regardless of whether the polymer is PVC plastisol that undergoes solvation and fusion, caprolactam that undergoes reaction to produce a thermoplastic nylon, or a two-part thermoset that undergoes reaction to produce a thermosetting product, it is imperative that the liquid charge form a uniformly thick liquid layer on the surface of the mold, i.e., solid body rotation, *before* the liquid viscosity increases to the point where liquid flow is impossible (Figure 6.39).

In addition, rotational speeds and rotational ratio are important factors. It appears that the same major-to-minor axis rotational ratios used for powders are applicable for liquids. Of course, the rotational speed, ω, must be sufficient to allow the liquid to be uniformly deposited on the mold wall prior to gelation.

The initial mold temperature is important if external heat is necessary to initiate the solidification step. PVC plastisol is charged into a cold mold, which is then transiently heated by placing the rotating mold assembly in a hot air oven. Caprolactam is polymerized only when the liquid is charged into a hot mold. Polyurethane reaction is highly exothermic and so the reaction can take place in an adiabatic or unheated mold. Unsaturated polyester resin reaction is slow and so the mold should be warmed prior to charging. Care must be taken, however, to avoid overheating the resin before it is uniformly coated on the mold. Again, polyesters gel into intractable states prior to exotherming.

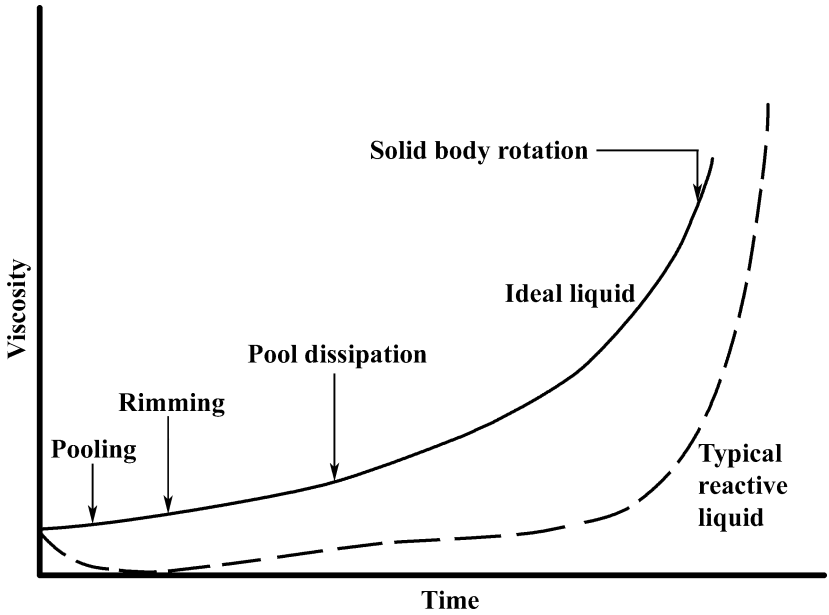

Figure 6.39 Time-dependent viscosities for an ideal fluid and a typical rotationally moldable reactive liquid. Typical fluid flow phenomena also shown

As noted above, corner radii need to be as generous as possible and the mold position relative to the axes of rotation can dramatically affect the wall thickness uniformity.

Even though liquid polymer rotational molding preceded solid powder rotational molding by many years, it remains the more difficult process. Confounding this, the fundamental understanding of the liquid process has had only sporadic attention. As a result, rotational molders are required to experiment extensively to determine the proper forming conditions.

6.32 Foam Processing

Although the idea of foaming rotationally molded polymers is not new,[118] there is now a growing interest,[113–117] since, as discussed in Chapter 7, foamed rotationally molded parts provide high stiffness at low weight. Currently, there are a number of ways of making rotationally molded foam parts. In the majority of cases, the product is manufactured in a sequential manner, as detailed below. Essentially the skin layer is formed first and a second, foamable layer is added by briefly stopping the mold rotation or by activating a drop box which is attached to the mold and which contains the foamable polymer. Typical examples include canoes and outdoor furniture. In some cases, a bag containing the foamable polymer is placed in the mold with the unfoamable polymer powder that will coalesce and densify into the solid skin. The bag polymer is carefully chosen so that it will not melt and release the foamable polymer until the skin layer has formed. In other cases, the part is manufactured in a single step process, as detailed below.

If the interior foam is required for insulation purposes, rather than for stiffness enhancement, low-density polyurethane (PUR) foam is injected into the finished rotationally molded part. Little or no stiffness improvement is seen unless the inner surface of the part is treated to allow the PUR to bond to it. In the following sections, only the use of foaming agents to produce stiff sandwich structures with solid skins and high-density foamed cores are considered.

There are two ways of generating the gases needed to foam molten polymers:

1. Physical foaming agents, including hydrocarbons, halogenated hydrocarbons, atmospheric gases such as carbon dioxide and nitrogen, and even water
2. Chemical foaming agents, which are typically thermally unstable pure chemicals

In the thermoplastic foams industry, chemical foaming agents are used to produce higher density foams, where the density reduction is no more than 50% and in many cases typically 20% to 30%. Physical foaming agents are used to produce low density foams, where the density reduction can be as much as 95%.

For most commercial rotational molding products, density reduction is no more than 50% and therefore chemical foaming agents are used. Foams are

produced by adding these thermally unstable pure chemicals, called *chemical blowing agents* (CBAs), or *chemical foaming agents* (CFAs), to the polymer, either by compounding them into the polymer prior to pelletizing and grinding, or by adding them as dry powder directly to the polymer powder at the mold filling station. Compounding is always desired.* Table 6.15 indicates the typical chemicals used to foam plastics in rotational molding.

Table 6.15 Chemical Foaming Agents

Chemical Name	Decomposition Temperature (°C)	Gas Yield (cm^3/g)	Type	Typical Polymers Foamed
Azodicarbonamide (AZ)	195–215	220	Exo	EVA, HDPE, LLDPE, LDPE, PP, TPE, FPVC
4,4'-oxybisbenzene sulfonyl hydrazide (OBSH)	160	125	Exo	HDPE, FPVC
p-toluenesulfonyl semicarbizide (TSS)	228–235	140	Exo	EVA, HDPE, LLDPE, LDPE, PP, TPE, FPVC
5-phenyltetrazole (5-PT)	250–300	200	Exo	PP, PC
Sodium Bicarbonate ($NaHCO_3$)	100–140	135	Endo	LDPE, EVA, FPVC, TPE
Alkali Carbonate (Hydrocerol)	160+	100–160	Endo	LDPE, EVA, LLDPE, FPVC
Alkali Carbonate (Activex)	120	140	Endo	LDPE, EVA, FPVC
Alkali Carbonate (Safoam)	170–210	130	Endo	EVA, HDPE, LLDPE

6.32.1 *Chemical Blowing Agent Technology*

As noted, chemical blowing agents are thermally unstable pure chemicals.** There are two categories of CBAs:

1. Exothermic CBAs that give off heat while they decompose
2. Endothermic CBAs that take up heat while they decompose

* At 100 microns or so, CBAs are finer powders than rotational molding polymer powders at 500 microns. Many CBA powders are sticky or tacky, even at room temperature, and so tend to agglomerate or stick together. Even if the CBA powder is freely flowing, the finer CBA particles will be filtered through the coarser polymer particles, leading to a nonuniformly foamed structure, typically with coarser cells at the mold surface, and hence, poorer part appearance surface.

** For more details about CBAs, please see Ref. 100.

Each CBA decomposes relatively rapidly at a very specific temperature. For example, azodicarbonamide or AZ, the most popular exothermic CBA, decomposes completely over the temperature range of 195–215°C (380–420°F). About 35% (wt) of the decomposition product is a mixture of nitrogen (65%), carbon monoxide (31.5%), and carbon dioxide (3.5%). Sodium bicarbonate ($NaHCO_3$) is the most popular endothermic blowing agent, decomposing in a temperature range of 100–140°C (210–285°F) and generating carbon dioxide and water vapor.

The amount of gas generated by the decomposition of a blowing agent is typically given in cm^3/g of blowing agent at standard temperature and pressure. As examples, AZ generates 220 cm^3/g of blowing agent and $NaHCO_3$ generates about 135 cm^3/g of blowing agent. Other blowing agents are detailed in Table 6.15.

It is important to realize that a CBA can only be effective when the polymer is densified into a monolithic liquid layer before the CBA decomposes.

As an example, consider HDPE as the polymer to be foamed. As noted in Chapter 2, HDPE has a melting temperature of about 135°C. According to Table 6.16, AZ is an acceptable CBA but $NaHCO_3$ would probably decompose before the polymer was fully liquefied. On the other hand, if a PVC plastisol is to be foamed, the polymer temperature might never reach the decomposition temperature of AZ, in which case a lower CBA such as $NaHCO_3$ or *p*-toluene sulfonyl hydrazide or TSH should be used.

Table 6.16 Effect of Dosage of Azodicarbonamide (AZ) on Foaming Characteristics of MDPE[102]

CAB Level (% wt)	Wall Thickness (mm)	Density (kg/m^3)	Density Reduction (%)	Wall Thickness Increase (%)
None	3.5	931	None	None
0.2	6.0	639	32	42
0.5	7.8	451	52	56
0.8	10.8	373	60	68
1.0	13.0	310	68	73

The exact CBA dosing level depends on several factors. An estimate of the maximum density reduction that might be achieved is as follows. If all the gas generated by the decomposition is converted to gas that resides in the foam cell, the volume of gas in the foam cell is the product of the dosage level and the amount of gas generated.

Example 6.4

Determine the minimum density for a 1000 kg/m^3 density polymer foamed with 1% (wt) azodicarbonamide. Then determine the minimum density if foamed with 1% (wt) $NaHCO_3$.

Solution

For 1% (wt) AZ, the amount of gas generated per unit weight of polymer is 220 cm^3/g CBA × 0.01 g CBA/g polymer = 2.2 cm^3/g polymer. The volume of unfoamed polymer is 1.0 cm^3/g.

Therefore the total volume of foamed polymer is 1.0 + 2.2 = 3.2 cm^3/g polymer or the foamed polymer would have a minimum density of 0.30 g/cm^3, for a density reduction of 67%.

If 1% (wt) $NaHCO_3$ is substituted for AZ, the total volume of foamed polymer is 1.0 + 1.35 = 2.35 cm^3/g polymer or the foamed polymer would have a minimum density of about 0.42 g/cm^3, for a density reduction of about 58%.

Understand, however, that not all the gas generated by the decomposition of the CBA remains in the cell. Some may have escaped during compounding. And some escapes to the inner mold cavity atmosphere and some is dissolved in the polymer. And certainly not all the CBA fully decomposes. A material balance on the blowing agent is used to determine the amount of gas available for foam production:

$$\frac{\left[1+f(BA)\right]}{\rho_f}-\frac{1}{\rho_p}=\frac{\left[f(BA)-b\right]RT}{MP} \tag{6.87}$$

where (BA) is the blowing agent concentration in g/g polymer, ρ_f and ρ_p are the densities of the foam and unfoamed polymer at the termination of expansion, T and P are the foam temperature and cell gas pressure at the termination of expansion, f is the fraction of gas that has escaped to the environment, R is the gas constant, and M is the molecular weight of the blowing agent.

Dramatic time-dependent changes in cell characteristics are anticipated during bubble growth in the wall of a rotationally molded part during the final stage of heating, thermal inversion, and cooling to the recrystallization temperature. Typically, in rotational molding, more than 50% of the gas generated is lost to the atmosphere.[101] CBA dosages should be between 0.5% (wt) and 1% (wt) in order to achieve polymer density reductions of, say, 25%. Table 6.16 shows the effect of chemical blowing agent dosage on density reduction and wall thickness of a polyethylene part.

The mechanics of bubble nucleation and growth are outside the scope of this work and are found detailed elsewhere.* However, a brief overview is given here. There are four stages to the foaming process:

Bubble Nucleation. As noted, CBAs are solid thermally unstable chemicals that are distributed throughout the continuous polymer phase. When the liquid polymer temperature reaches the decomposition temperature of the CBA, gas is evolved at the surface of each piece of CBA or on solid micron-sized inorganic particles such as talc and TiO_2 that have been added as deliberate nucleants.

Inertial Bubble Growth. The molecules of gas generated by CBA decomposition collect on the surface of the decomposing CBA or on solid surfaces such as the CBA residue or nucleants. When sufficient molecules have "clustered" in a given area, an interface between the gas and the polymer is formed, thus creating a microvoid that eventually, in one way or another, becomes part of a bubble. Gas molecules rapidly diffuse to the growing bubble interface and the plastic is stretched away from the nucleant site. The stretching resistance offered by the plastic is quantified as elongational or zero-shear viscosity, and this early bubble growth is referred to as "inertial bubble growth."

Diffusional Bubble Growth. As the bubble grows, the region around the growing bubble is quickly depleted of the gas needed to sustain growth. As a result, gas molecules from richer polymer regions must diffuse to the growing bubble site. Since the diffusional process is slower than the initial inertial growth process, the bubble growth slows dramatically. This bubble growth is referred to as "diffusional bubble growth." Bubble coalescence, where two bubbles merge into one, occurs during this time. Typically, inertial bubble growth occurs in milliseconds and bubbles grow from submicron size to 50 to 100 microns in size. Diffusional bubble growth takes seconds and bubbles grow from

* Please check Refs. 103-107 for more details.

50 to 100 microns in size to perhaps 500 microns in size, depending on the extent of bubble coalescence.

Terminal Bubble Growth. There are several ways of inhibiting or stopping bubble growth. One way is to quickly chill the foam. Another way is to simply restrict the amount of gas generated by restricting the amount of foaming agent used. No matter what technique is used, there is a strong reason why bubbles stop growing. Simply put, bubbles grow because the pressure in the bubble exceeds the pressure in the melt as given by Rayleigh's principle:

$$p_{\text{inner}} - p_{\text{liquid}} \geq \frac{2\gamma}{R} \tag{6.88}$$

where p_{inner} is the cell gas pressure, p_{liquid} is the pressure on the liquid surrounding the bubble, γ is the surface tension, typically 30 dynes/cm,* and R is the current radius of the bubble. For bubbles to grow, the left side of this equation must be much greater than the right side. Theoretically, when the left side is approximately equal to the right side,** bubbles should stop growing.

The rotational molding process sequence is not ideal for fine, uniform bubble growth for several reasons:

- The temperature through the liquid layer is not isothermal. As a result, bubbles form and grow first in the polymer layer closest to the inner mold wall. Then foaming proceeds inward. Since the thermal conductivity of the blowing gas is always much lower than that of the polymer, the foaming layer acts to thermally insulate the yet-to-be-foamed liquid from the increasing inner mold wall temperature. As a result, the rate of evolution of gas decreases as time continues.

- The average temperature of the liquid layer continues to increase with time. The inertial stage of bubble growth is inversely related to polymer viscosity. Increasing polymer temperature means decreasing

* But in certain cases, this value can be much lower.

** For dynamically growing bubbles, the right side needs terms describing the viscoelastic nature of the polymer. In general, these terms are relatively small and so the pressure differential is usually quite small, meaning that p_{inner} is approximately equal to p_{liquid} at the time of cessation of bubble growth. Even though most of the theoretical work has been done for polymer processes such as extrusion, and even though the rotational molding process is quite unique in that the polymer pressure is essentially atmospheric throughout the molding process, and the melt temperature may be actually increasing with time, the theoretical concepts seem to still be valid.

polymer viscosity and more rapid bubble growth, as time moves on. In addition, diffusional coefficients of gases in polymers are strongly dependent on temperature. Increasing polymer temperature means increasing rate of gas diffusion to the growing bubble. Both effects cause bubble growth rates to accelerate as time in the oven continues. Very rapid bubble growth rates are known to lead to excessive bubble coalescence and hence, very large foam bubbles. This is reviewed in Table 6.17 for two different foaming agents and varying oven conditions.

Table 6.17 Effect of Oven Conditions on Foaming of HDPE[108]
(OBSH = *p,p′*-oxybisbenzene sulfonyl hydrazide; AZ = azodicarbonamide)

CBA Level (% wt)	CBA Type	Oven Temperature (°C)	Oven Time (min)	Comments
1	OBSH	246	10	Good inside skin, limited foaming
1	OBSH	246	12	Good inside skin, good foam
1	OBSH	246	14	Fair inside skin, good foam
1	AZ	260	10	Good inside skin, little foam
1	AZ	260	12	Good inside skin, good foam
1	AZ	260	14	Poor inside skin, overblown with coarse cells

- Rotational molding is a pressureless process. It is well-known that to prevent the formation of gross bubbles, the gas must be fully dissolved in the polymer prior to initiation of the bubble nucleation and growth process.[109] The concept of conducive pressure to foam has been defined to quantify this condition. Basically, the pressure needed to keep a specific gas dissolved in a specific polymer is given in terms of Henry's law:*

$$S = H \bullet P \tag{6.89}$$

* Note that Henry's law was discussed earlier in the bubble dissolution section. It is somewhat ironic that when attempting to make a bubble-free monolithic part, it is very difficult to rid the melt of bubbles, and when trying to make a foam, it is very difficult to generate very small bubbles

where P is pressure, S is solubility of the gas in the polymer in [cm^3(STP)/g plastic] and H is the proportionality called Henry's law, [cm^3(STP)/atm g plastic], which itself is temperature-dependent:

$$H(T) = H_0 e^{-E_0/RT} \tag{6.90}$$

where H_0 is a pre-exponential constant, E_0 is the activation energy for solubility, R is the gas constant and T is the polymer temperature in K.

Note that solubility is linearly dependent on pressure applied to the polymer. For rotational molding, only atmospheric pressure is applied to the polymer. Therefore, in conventional rotational molding, very little gas is dissolved in the plastic. This simply means that bubbles are formed as soon as the gas is generated by decomposition of the CBA. Since the CBA is typically discrete solid particles having dimensions of greater than 10 microns and typically on the order of 150 microns, this implies that there are relatively few sites for bubble nucleation. This in turn implies that the cell structure in the final foamed part will be relatively coarse.

- Rotational molding cooling practice serves only to promote coalescence. Recall from the discussion earlier in this chapter that once the mold assembly exits the oven, it is imperative that cooling proceed slowly as the thermal profile in the polymer liquid inverts. And further, it is imperative, for slowly crystallizing polymers in particular, that cooling proceed slowly through the recrystallization step, so as to achieve an optimum level of crystallinity. The continuing delay in cooling the foam structure to a temperature where further bubble expansion and coalescence cannot occur can only result in large cells.

This does not mean that it is not technically possible to produce foamed rotationally molded parts. It means that to achieve good small-celled cellular products, some changes must be made in both processing conditions and polymer characterization. For example, as noted in Chapter 2 on polymer specification, the best melt index or MI for rotational molding grade polyethylene should be around 5. For foamable polyethylene, a lower melt index or MI is recommended. Typically an MI of about 2 should have sufficient melt strength to minimize gross bubble coalescence. Polypropylene offers an even greater challenge, since not only does the PP need additional melt strength to minimize bubble coalescence but care must be taken during the recrystallization

step to ensure that the PP foam is crystallized to the same level throughout the part wall.*

6.32.2 *Single Layer vs. Multiple Layer Foam Structures*

Although coarse cell structure does not detract from the mechanical strength of a foamed part,** the part appearance may be quite unsatisfactory for all but the most utilitarian applications, such as flotation devices and dunnage. Single layer foamed surfaces can be painted or decorated with appliques in areas of interest. These techniques are not feasible for many applications such as industrial tanks and consumer products such as canoes and kayaks. As a result, techniques have been developed to rotationally mold two- and three-layer structures in which either or both part surfaces are made of compact polymer, that is then backed with foamed polymer. There are two commercial approaches to multilayer foamed structures.

6.32.2.1 *One-Step Process*

Basically, in the one-step process, sometimes called one-shot foaming, two types of polymer powders are added to the mold at the same time. One polymer contains no blowing agent. The other polymer is a compound containing the CBA. Ideally, the skin and core polymer should be chosen so that their thermal, rheological, and physical characteristics allow easy separation during the tumbling of the mixture in the mold. For example, the foamable, core polymer might have a higher melting temperature and coarser particle size than the unfoamable, skin polymer. This can be achieved if unfoamable polymer is LDPE or even EVA and the foamable one is HDPE. This combination would allow the unfoamable polymer to preferentially tack and coalesce on the mold surface before the foamable polymer reaches its tack temperature. Theoretically, the structure formed should have an unfoamed skin and a distinct, foamed core. Practically, the foamable polymer particles stick to the tacky or sticky unfoamed polymer. The typical product has a skin that contains substantial bubbles and a gradual density change from near-unfoamed density on the mold side to foamed density on the inside.

In general, it is not a trivial matter to achieve good separation of the skin and core layers. A number of techniques have been patented in an attempt to

* As of this writing, very few foamed PP parts have been commercially produced.

** The strength of foamed structures is discussed in detail in Chapter 7.

overcome this limitation. Not every system works with every mold geometry. In certain molds, the foamable polymer may be trapped against or near the mold wall where the excessive residence time and temperature causes foaming, resulting in poor outer skin on the molded part.

One technique uses quite large coated foamable polymer particles, with the very smooth coating being brittle-friable with a very high melting temperature. The particles are sufficiently smooth and large that relatively few stick to the liquefying unfoamable polymer layer. When the CBA decomposes, internal gas pressure ruptures the friable coating and the now-sticky foaming polymer sticks to the unfoamable polymer layer.

It appears that for one-step systems to succeed regularly, attention needs to be paid to mold design to minimize dead zones where the foamable polymer may get trapped, and to processing conditions, particularly rotational speeds, in order to minimize premature foaming.

6.32.2.2 *Two-Step Process*

In this process, polymer powders are sequentially added to the mold cavity. In an earlier process, the outer skin unfoamable polymer was added and rotationally molded to a liquid state in a normal rotational molding fashion. Then the mold was exited from the oven, a trap-door was opened in the hot mold and a second, foamable powder was manually added. The entire mold assembly was then readmitted to the oven and reheated until the second polymer liquefies and foams. A newer technique uses a drop box (Figure 6.40). A drop box is an insulated container that fits over a mold opening or trap-door, and is put in place after the unfoamable polymer has been charged to the mold. The foamable powder is then placed in the drop box and an electronically activated trap-door relay is set. The mold assembly is oven-heated until the unfoamable polymer has coalesced and liquefied into a monolayer. Then the relay is activated, dropping the foamable polymer charge into the still-rotating mold assembly. A product produced this way always shows a distinct skin-core interface. If both inner and outer surfaces must be smooth, the two-step process is extended with two drop boxes, the first containing the foamable polymer and the second the inner skin polymer. The correct time for activating the drop box is easily determined if temperatures are being monitored inside the mold. If temperature is not monitored, then experimentation is needed to ensure that the foamable polymer is fully liquefied and foamed prior to activating the second drop box relay. The skin-core-skin product thus

produced resembles a T-beam or an I-beam in its mechanical performance. This is detailed in Chapter 7 on product design.

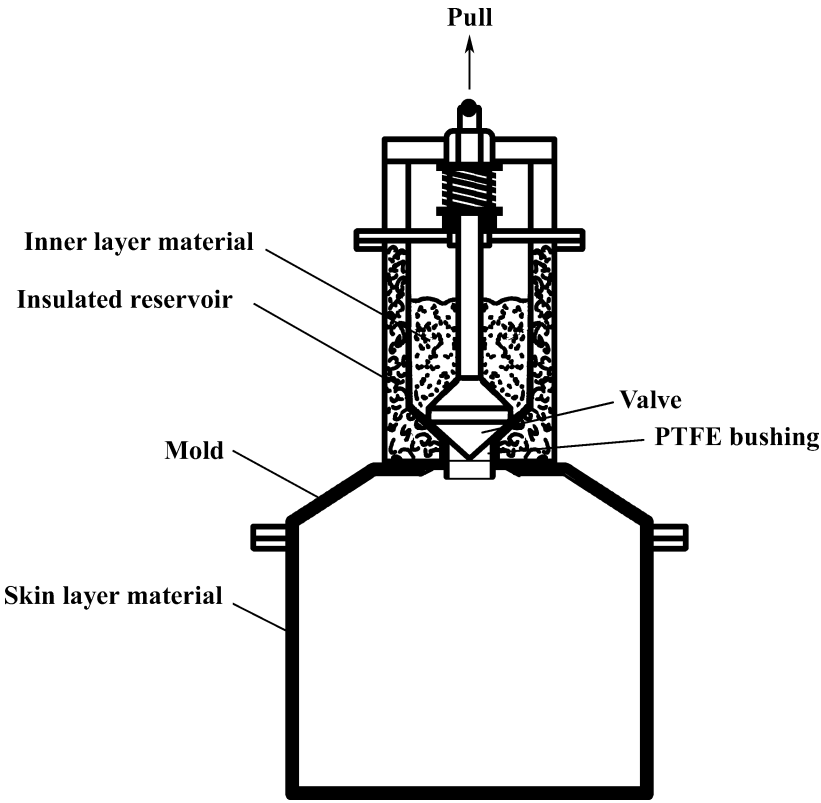

Figure 6.40 Typical insulated drop box for multistep foaming, courtesy of Wheeler-Boyce, USA

6.32.2.3 *Drop Boxes — Inside or Out?*

In the discussion above, it was stated that the drop box was affixed to the *outside* of the mold. For many reasons, this is the preferred orientation. However, it must be noted that the drop box may be placed at right angles to the attitude of the mold and its structure may be so large that the mold cannot be properly swung. The external drop box fits best if the product has one dimension that is much smaller than the other two, such as a canoe, and if the trapdoor or access way is not in the smaller dimension. If the product has about the same dimensions throughout, such as a tank, and if the access way is

sufficiently large, the drop box can be placed *inside* the mold cavity,[110] with the mounting bracket affixed to the access way edges. As with the outside drop box, the inside drop box must be heavily insulated to prevent melting the polymer and activating the CBA.

6.32.2.4 *Containerizing Inner Layers*

Recent work on multilayer structures has focused on "containerizing" the second polymer. One method encloses the second polymer in a plastic bag.[111] The plastic bag material has a higher melting temperature than the polymer powder that makes up the outer skin. As a result, the bag simply rotates with the mold while the polymer powder coalesces and densifies. The bag then melts and the polymer making up the second layer is free to coalesce and densify or foam. Many discrete layers can be built up by proper bag material selection. This approach offers flexibility in product design that could extend, as an example, to multilayer structures with UV-resistant skins, short glass fiber-reinforced inner layers, foamed cores, and high-ESCR inner layers.

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7 MECHANICAL PART DESIGN

7.0 Introduction

The objective of any rotational molding scheme is to produce a part that meets all end-use requirements. This chapter focuses on the mechanical performance of rotationally molded parts, but includes some design philosophy and part quality issues such as dimensional stability. For a more in-depth view of aesthetic rotationally molded part design, the reader is referred to Ref. 1, a recent monograph on the subject. This chapter will refer to this resource work where necessary to emphasize the interrelationship between mechanical performance and actual part quality.

7.1 Design Philosophy

The product designer must approach rotational molding part design the same rational way that he/she approaches part design when using other molding technologies. Three important concerns that must be met when manufacturing any product:

1. Will the finished part meet all required and specified design criteria?
2. Can the part be produced at the minimum cost for the projected market size?
3. What are the consequences if the part fails to meet minimum requirements?

The implications of the last question influence many product designs today. Parts fail for many reasons including:[2]

- Fracture due to poor product design for the application, environmental degradation, embrittlement, and improper use of regrind
- Creep
- Crazing and stress cracking due to internal or external chemical attack or poor product design
- Fatigue, either through periodic or aperiodic tensile, flexural, or shear loading, or through vibration, or repeated impact

- Interfacial failure between layers due to poor adhesive selection or improper fusion at the interface
- Warpage or distortion due to poor manufacturing procedure, severe use, or gradual environmental attack
- Shrinkage due to improper manufacturing conditions, failure to relieve frozen-in stresses, or excessive environmental temperature
- Change in appearance, including color change due to improper selection of pigment, migration of dyes, aging, improper processing temperature, change in surface gloss, or change in transparency due to environmental conditions
- Odor and toxicity due to migration of additives from polymer, environmental or chemical attack of polymer and/or additives in polymer
- Failure due to migration of cracking elements from neighboring materials, including adhesives and machine and cutting oils

Probably of greatest concern to the designer today is failure due to consumer misuse that results in injury and litigation. It is impossible to design against all types of misuse, especially where the product is extended beyond the designer's original intent. The designer must include safety factors and must conduct an audit of sources of inherent product weaknesses prior to issuance or commercialization of the product. Where possible, the part should be designed to fail safely when used beyond design conditions.

The designer should consider some or all of the following design elements when considering rotational molding for a particular application:[3]

- Field of application, such as food contact, materials handling, and consumer use
- Part function, such as decorative, protective, container for liquids or solids, and structural use
- Environmental contact, including temperature, nature of the environment (corrosiveness or potential solvation), and the nature of the loads
- Part appearance such as surface quality and texture, trim line appearance, and whether the part is nonappearance

- Cost balanced against material requirements and number of parts required
- Competitive processes such as injection molding, thermoforming, and blow molding
- Part design limitations including strength, load characteristics, length of service, and potential abuse
- Government regulations including standards such as those of the Food and Drug Administration (FDA), Environmental Pollution Agency (EPA), and National Sanitation Foundation (NSF), and fire retardancy
- Interaction with other elements, including assembly requirements, methods of fastening such as adhesives and snap fits, and metal-to-plastic concerns such as differential thermal expansion

Once the designer has established the bases for product design, he/she must determine whether the part can be rotationally molded. Some of the reasons for producing parts via rotational molding are:

- Very large surface to thickness ratios are possible
- Process is ideal for a few, very large parts
- Wall thickness is uniform
- Molds are relatively inexpensive
- Chemically crosslinked polyolefins offer chemically resistant products
- Polyethylene is the material of choice for the application
- The product is a container
- The part requires little or no postmold decoration

The designer must also identify reasons for *not* rotationally molding the part. Some of these reasons are:

- The polymer specified is not available as a powder and cannot be ground into powder without significant thermal damage
- The polymer specified cannot be subjected to the high time-temperature environment of rotational molding. The nature of rotational molding

forces a very limited choice of polymers, with polyethylene being the primary polymer of choice

- The part requires high filler or fiber loading
- The part requires a polymer with a thermally sensitive pigment or fire retardant
- Many parts are needed requiring short cycle times and low labor costs, conditions traditionally unmet by rotational molding
- The part requires sharp corners or very small radius dimensions. Rotational molding works best for large-radii parts that may not be aesthetically appealing
- Part tolerances are too tight for rotational molding

For many parts, full-scale product testing is difficult or impossible. The designer must simulate the environmental conditions in small-scale or laboratory tests. In certain instances, the product design can be tested using mathematical techniques such as finite element analysis (FEA).[4]

7.2 General Design Concepts

Of the three competing single-sided processes — thermoforming, blow molding, and rotational molding — only rotational molding has the potential to yield uniform wall thickness for even the most complex part. Very simply, this is because polymer powder will preferentially stick to the hottest surface. So long as polymer powder gets to all surfaces of the mold cavity, the adhesion will occur uniformly. This does not imply, however, that every rotationally molded part has uniform wall thickness. Mold walls may have locally hot and cold surfaces. Powder flow may be restricted in some areas of the mold and may become trapped in others.

Rotationally molded part design has been detailed elsewhere.[1] The serious designer should carefully review this source for functional reasons behind certain aesthetic design elements. Certain general guidelines are useful, however, when considering the mechanical design aspects of rotationally molded parts. The major ones are given below:

- Polycarbonate and nylon powder must be kept very dry prior to molding, to prevent moisture pick-up. Moisture will degrade the polymer,

resulting in lowered physical properties, particularly impact. Moisture will also lead to the formation of microbubbles, which act as stress concentrators. The presence of bubbles may also lead to reduced impact strength.

- Solid ribs cannot be successfully rotationally molded. Hollow ribs, where the rib width-to-depth ratio is greater than one, are recommended.
- Shallow undercuts are possible with polyethylene and polypropylene. Deep undercuts are possible with PVC plastisol. Undercuts are not used when molding stiffer polymers such as polycarbonate.
- Care must be taken when pulling a warm polypropylene or nylon part from the mold, since the polymer may not be fully crystallized and any distortion may become permanent.
- When determining final part price-performance ratio, thinner part walls mean shorter molding cycle times and lower material costs. However, stiffness reduces in proportion to the part wall thickness to a power of three.
- Flat-panel warpage is minimized through part design. Crowns, radial ribs, domes, stepped surfaces, and corrugations will act to minimize warpage.
- If warpage is severe, the cooling rate during molding must be reduced. If warpage continues to be severe, mold pressurization may be required.
- Rotational molding is used to make parts with parallel or near-parallel walls. The distance between the walls must be sufficient to allow for powder flow and to minimize bridging. The distance between walls should be at least three times the desired wall thickness. Five times is recommended.
- If the part is bridged in a given region, it will take longer to cool in that region. The result will be generation of internal voids and differential shrinkage, which may lead to part distortion and localized sink marks. For the most part, rotational molding yields stress-free parts. However, in bridged areas, local stresses may be quite high and may lead to local part failure in fatigue or flexure.

- If the depth of the outer mold cavity is greater than the width across the cavity, heat transfer to the bottom of the cavity may be restricted. The result will be that the wall thickness on the inside of the double wall may become very thin, especially at the very bottom of the wall. Stationary baffles on the mold surface are effective for cavities with depth-to-width ratios less than about 0.5. Forced air venturis are currently recommended for deeper cavities.

- Insulation pads are applied to a local area to minimize thickness in that area. Regions where little or no plastic is desired would include areas to be trimmed on the final part. If the part needs to have a thicker wall in a given area, the mold wall is made thinner or the mold is made of a higher thermal conductivity metal in that area.

- Small-radius inside mold corners typically take longer to heat and cool and therefore part walls can be thinner in corners than in adjacent sidewalls. Generous radii mitigate this problem. Small-radius outside corners tend to heat and cool more rapidly and therefore part walls can be thicker in corners than in adjacent sidewalls. Again generous radii mitigate this problem.

- Structural strength is obtained primarily through addition of stiffening elements such as chamfered or large-radiused corners, hollow gussets, hollow ribs, and round or rectangular kiss-offs (or almost-kiss-offs). For hollow double-wall parts such as decks and doors, it is desired to have indentations such as ribs and kiss-offs molded in both surfaces. This aids in energy distribution to and minimizes thinning at the bottoms of the ribs and kiss-offs. The widths of the openings of the indentations must be increased if the design requires that one surface be indentation-free. Addition of fillers or reinforcing fibers as stiffening agents is not recommended in rotational molding.

- Rim stiffening is achieved by adding ribs just below the rim, or by flanging the rim with either a flat flange or a U-shaped flange. A metal reinforcing element, such as a hollow conduit, can be placed in the mold prior to powder filling. This allows the reinforcing element to be an integral part of the structure. The designer must remember that plastics have about 10 times the thermal expansion of metals and that the metal must be affixed so that it does not create concentrated stresses on the plastic part during heating and cooling.

- As detailed below, there are many reasons to have large-radiused corners. Outside corners on parts tend to shrink away from the mold wall and so have low residual stresses. Inside corners on parts tend to shrink onto the mold wall and so have greater residual stresses than neighboring walls.

- Deep undercuts are formed around removable inserts or core pins. These are made either of a high thermal conductivity metal such as aluminum for a steel mold or copper-beryllium for an aluminum mold, or are hollowed out.

- Rotationally molded parts usually are formed in female molds at atmospheric pressure, with shrinkage allowing the part to pull away from the mold. This allows parts to be molded with no draft angle and thus vertical sides.

- Although rotational molding uses no pressure, the polymer against the mold wall is molten. As a result, it is possible to transfer quite fine texture from the mold wall to the finished part. Competitive processes such as thermoforming and blow molding require differential pressures of 3 to 10 atmospheres to achieve similar results.

- Deep undercuts, including complex internal threads, are possible through proper mold design.[5]

- Inwardly projecting holes can be molded in using core pins. If the pin is long enough or if it is solid, the polymer will not cover the pin end. If the pin is short, hollowed out, or is a thermal pin where heat is rapidly conducted down the pin length from the oven air, the hole will be blind. Large diameter outwardly projecting holes are possible, as long as the diameter-to-length is less than one and the diameter-to-wall thickness is greater than about five. Outwardly projecting holes are molded closed and are opened with mechanical means such as saws or routers. Holes should be spaced about five wall thicknesses from each other.

- Detents molded into the part wall provide locators for drills and hole saws.

- Both internal and external threads can be rotationally molded into parts. The recommended thread design is the "modified buttress thread profile" or Acme thread. For fine-pitched, sharp threads, or for small-diameter threads, an injection-molded thread assembly is placed in

the mold prior to powder filling. The powder melts and fuses the assembly to the part body.

- In many instances, the rotationally molded part must be assembled to other parts using metallic screws or fasteners. Metal inserts have been developed especially for rotational molding. These inserts, usually of a high thermal conductivity metal, are placed in the mold prior to powder filling. Powder melts and fuses the insert to the part body. As the polymer shrinks, it is compressed around the insert, holding it in place. However, the metal prevents the polymer from shrinking fully. As a result, residual stresses are imparted in the insert region. These stresses can be a source of part failure during use. To minimize webbing and undue stress concentration, metal inserts should be three to five wall thicknesses away from corners.

7.3 Mechanical Design

The arithmetic for determining final part wall thickness from mold geometry and powder bulk density was detailed in Chapter 5. As it was pointed out, so long as the mold is heated uniformly everywhere, rotationally molded parts usually have inherently uniform part wall thicknesses. This is in direct contrast to blow molding and thermoforming, where the polymer is placed against the mold surface in a differential fashion that is strongly dependent on mold geometry. Of course, local thickness in rotational molding can be effected if a portion of the mold is shielded or insulated from the circulating air, or if the mold contains acute angles or parallel walls that are very close together, or if the mold has a local heat sink or an overhang that prevents the powder from contacting the heated mold surface. Typically, the final part wall thickness is determined from the required mechanical strength of the part and the selection of the polymer that meets the physical and environmental requirements of the product.

The mechanical strength of a rotationally molded part must always be considered in part design, whether the product is a child's water slide, a fuel tank for a military vehicle, or an access door for an electrical cabinet. Mechanical performance of polymer parts is best understood in terms of the time during which the part is subjected to load. Moderate term loading is exemplified by flexural, compressive, and tensile properties such as modulus and strength. Short term loading is characterized by impact. Long term loading is characterized in terms of stress relaxation, creep, and flexural fatigue. Although

the general subject of polymer response to mechanical loading is outside the scope of this work,[6,7] certain aspects of mechanical design are needed to understand how rotationally molded parts should behave under load.

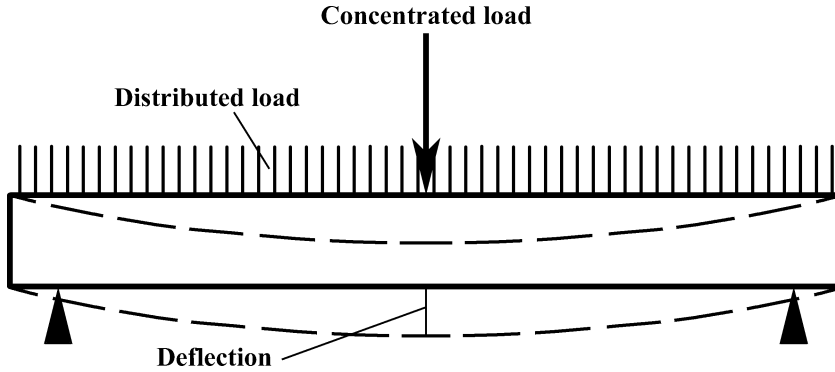

Figure 7.1 Three-point beam bending schematic with concentrated and distributed loads

7.3.1 *Three-Point Flexural Beam Loading*

Consider a simple beam of rectangular cross-section, supported on two ends, and loaded with either a concentrated load or a uniform load (Figure 7.1). The maximum deflection, δ_{max}, is given in terms of the nature of the applied load , the polymer modulus, E, and the geometric features of the beam, such as its length, L, its width, b, and its thickness, h. The moment of inertia or the second moment of area, I, of a rectangular beam about its neutral axis, is given as:[8*]

$$I = bh^3/12 \tag{7.1}$$

Stiffness is given as the product of the polymer modulus and the moment of inertia:

$$S = EI \tag{7.2}$$

For uniform load, w (weight per unit length), the maximum deflection is:

$$\delta_{max} = \frac{5wL^4}{384EI} = \frac{60wL^4}{384Ebh^3} \tag{7.3}$$

* Throughout this chapter, I will be referred to as the "moment of inertia."

For a concentrated load, P, centered in the middle of the span ($L/2$), the maximum deflection is:

$$\delta_{max} = \frac{PL^3}{48EI} = \frac{PL^3}{4Ebh^3} \tag{7.4}$$

Note the strong dependence on wall thickness (to the third power). Consider the case where the wall thickness tolerance is ±10%. The relative effect on deflection is ±30%. If the wall thickness tolerance is ±20%, the effect on deflection is ±60%. This is the technical justification for specifying *minimum* wall thickness in product design rather than *nominal* wall thickness.

7.3.2 *Cantilever Beam Loading*

In certain instances, the rotationally molded part may be used in cantilever (Figure 7.2). That is, it may be fastened on one horizontal end and allowed to deflect under load. For a rectangular beam under uniform load, the maximum deflection is:

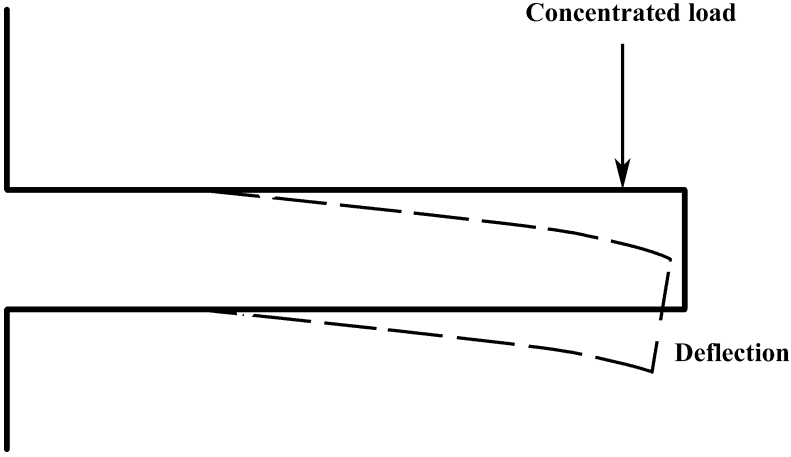

Figure 7.2 Cantilever beam geometry with concentrated load

$$\delta_{max} = \frac{wL^4}{8EI} = \frac{3wL^4}{2Ebh^3} \tag{7.5}$$

or the cantilever beam deflects nearly 10 times more under load than does the simply supported beam of the same geometry. Similarly, for a rectangular beam under concentrated load at its mid-span ($L/2$), the maximum

deflection is:

$$\delta_{\max} = \frac{PL^3}{3EI} = \frac{5PL^3}{4Ebh^3} \tag{7.6}$$

or the cantilever beam deflects 5 times more under this load than does the simply supported beam.

7.3.3 *Column Bending*

Frequently, a part wall is loaded parallel to its surface (Figure 7.3). Under this condition, the effect is sidewall bending or buckling. The extent of bending is analyzed either as simple plate bending or column bending. Consider a uniform column of length L, width b, and thickness h subjected to a buckling load P. The critical load for a column fixed on both ends is given as:

$$P_{\text{Euler, fixed}} = \frac{4\pi^2 EI}{L^2} = \frac{Ebh^3\pi^2}{3L^2} \tag{7.7}$$

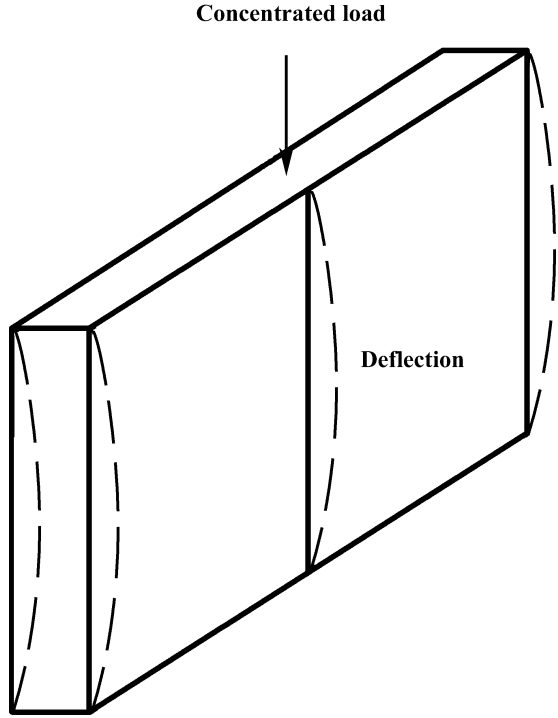

Figure 7.3 Edge loading of plate

so long as the neutral axis remains within the walls of the column. If the column is hinged or free to flex on both ends, the critical load, P_{critical} is one-fourth that of the fixed column:

$$P_{\text{Euler, free}} = \frac{\pi^2 EI}{L^2} = \frac{\pi^2 Ebh^3}{12L^2} \tag{7.8}$$

7.3.4 *Plate Edge Loading*

For a plate having a length L in the loading direction, W in the cross-direction, and a thickness h, the critical buckling force, F, for all surfaces fixed is given as:

$$F_{\text{critical}} = k\frac{E}{1-\nu^2}\left(\frac{h}{W}\right)^2 \tag{7.9}$$

where ν is Poisson's ratio, typically about 0.35 – 0.4 for polymers and k is given as:

k	W/L
7.7	1
6.7	0.5
6.4	0.33
5.73	0

Similar design equations are available for the cases where the loading edges are allowed to flex but the cross-loading edges are not, and where all edges are allowed to flex.[9] For all edgewise plate bending, the critical loading level is proportional to the square of the wall thickness, whereas for columnar bending and flexural plate bending, the critical loading level is proportional to the cube of the wall thickness.

7.3.5 *Hollow Beam with Kiss-Off Loading*

When a hollow structure, such as a door, is flexed, the load applied to one surface must be transmitted to the other in order to minimize deflection. In rotational molding, this is done through kiss-offs or near-kiss-offs (Figure 7.4).[10] For kiss-off ribbing, powder bridges the gap between the male portion of the lower mold half and the surface of the upper mold

half, thus forming a solid structure. When loaded, the load applied to one surface is immediately transferred to the other through the kiss-off. For near-kiss-off ribbing, the male portion of the lower mold half is sufficiently far from the surface of the upper mold half that powder can easily flow between. No bridge is formed. When one surface is loaded, it deflects until the gap between the two independent surfaces closes to zero. The load is then transferred from the top surface to the second surface as if the two were fused together. Stress concentration at the corners in kiss-off ribbing can be a problem and the thicker plastic at the bridge between the upper and lower surfaces will cool slower than the polymer on either side, resulting in a depression, witness mark, or sink mark over the kiss-off. Near-kiss-off ribbing is desired if the polymer is fatigue sensitive or if the unribbed surface must be relatively flat or of uniform texture.

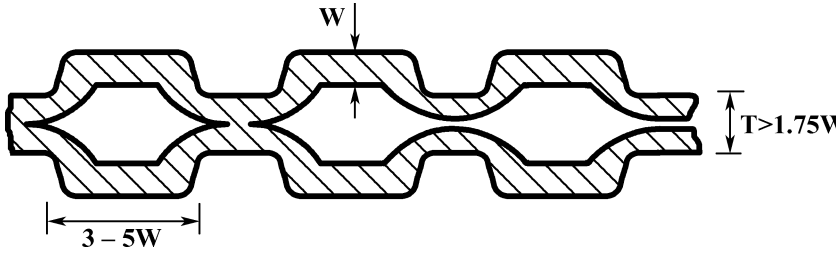

Figure 7.4 Kiss-off ribbing (left side) and near-kiss-off ribbing (right side), adapted from Ref. 10, with permission of copyright owner

The recommended maximum height of the hollow rib that forms the kiss-off is four times the part wall thickness, or $H < 4h$. The minimum width of the rib is three times the part wall thickness, with five times the recommended width, or $W > 3h$ and $W = 5h$. The flexural loading of a beam with kiss-offs is analyzed in terms of the stiffness:

$$S = EI \tag{7.2}$$

where, as before, E is the modulus of the polymer and I is the moment of inertia. For a solid beam, $I = bh^3/12$, as before. For a kiss-off-ribbed structure, the moment of inertia is altered to remove those sections that are void. Consider two similar structures, a ribbed structure and a hollow structure (Figure 7.5). Consider that the thickness of the walls for ribbed, hollow, and kiss-off structures is w and the space between the elements is a.

Consider the width b of the hollow structure to be made of n equal-sized

openings. Therefore $b = (n+1)w + na$. The moments of inertia are as follows:

Solid beam: $I_{NA} = bh^3/12$ (7.10A)

Hollow profile: $I_{NA} = [bh^3/12] - [na(h - 2w)^3/12] = [(n+1)wh^3 + nah^3 - na(h - 2w)^3]/12$ (7.10B)

where I_{NA} is used to denote the moment of inertia about the neutral axis of the structure.

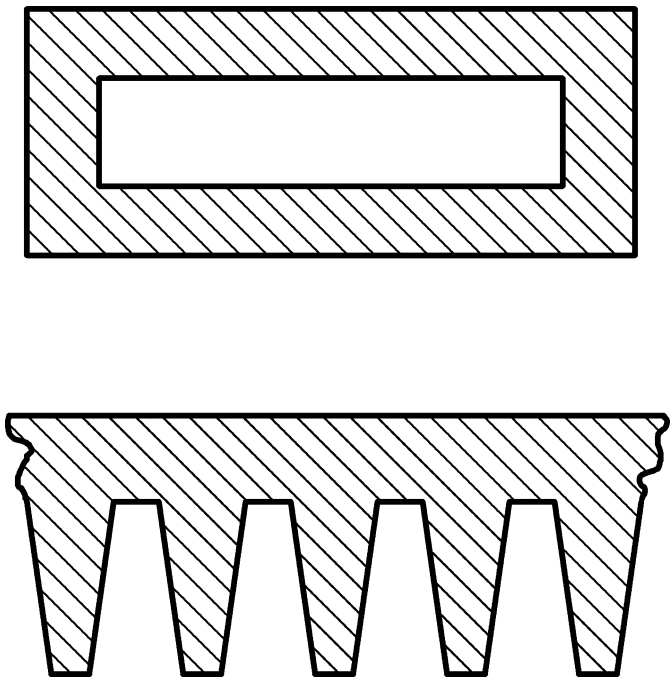

Figure 7.5 Schematic of hollow structure (top) and ribbed structure (bottom)

Since the ribbed structure is an asymmetric structure, its centroid is not at the mid-point between the top and bottom surface. Instead, the centroid, y_c, is given as:

$$y_c = \Sigma M_i/\Sigma A_i \equiv \Sigma A_i y_i/\Sigma A_i \quad (7.11)$$

where M_i is the moment of element i about an axis parallel to the bottom surface, y_i is the distance from the center of element i to that same axis, and A_i is the cross-sectional area of element i. Using the information given above:

Top plate: $M_{tp} = bw(h - w/2), \quad A_{tp} = bw$ (7.12A)

Rib: $M_r = w(h - w)^2/2, \quad A_r = w(h - w)$ (7.12B)

For $n + 1$ ribs, the centroid is given as:

$$y_c = [bw(h - w/2) + (n + 1)w(h - w)^2/2]/[bw + (n + 1)w(h - w)] \quad (7.13)$$

With this, the moment of inertia of a ribbed structure is given as:

$$I_{NA} = \Sigma I_{NA,i} \equiv \Sigma[I_i + A_i y_i^2] \quad (7.14)$$

Or:

$$I_{NA} = [bw^3/12] + bw[(h - w/2) - y_c]^2 + [(n + 1)w(h - w)^3/12] + (n + 1)w(h - w)[(h - w)/2 - y_c]^2 \quad (7.15)$$

This somewhat formidable equation is relatively easy to understand. The first two terms on the right represent the effect of the top plate on the moment of inertia. The last two terms on the right represent the effect of $n + 1$ ribs on the moment of inertia.

For the kiss-off structure shown in Figure 7.4, the moment of inertia is an alternating combination of the hollow cross-sectioned structure and the ribbed structure, redrawn as Figure 7.6.* Consider the case where there are n kiss-offs along the beam length b. If both surfaces have thickness w, the thickness of each kiss-off section is $2w$. The alternating elements of Figure 7.4 are redrawn to illustrate how the segments of the ribs are amassed in order to determine the kiss-off structure moment of inertia. The moments of inertia and areas of each segment are:

Top plate: $M_{tp} = b(h - w/2)w \quad A_{tp} = bw$ (7.16A)

Kiss-off: $\Sigma M_{ko} = na(h - 3w/2)w \quad \Sigma A_{ko} = naw$ (7.16B)

Bottom: $\Sigma M_{bot} = na(w/2)w \quad \Sigma A_{bot} = naw$ (7.16C)

Ribs: $\Sigma M_r = 2nw(h - w)^2/2 \quad \Sigma A_r = 2nw(h - w)$ (7.16D)

The centroid is given by summing the ratios of M_i to A_i:

$$y_c = \frac{[b(h - w/2)w] + [na(h - 3w/2)w] + [na(w/2)w] + [2nw(h - w)^2/2]}{bw + 2naw + 2nw(h - w)} \quad (7.17)$$

* Typically, kiss-offs have substantial draft. No draft angle has been assumed for the arithmetic that follows.

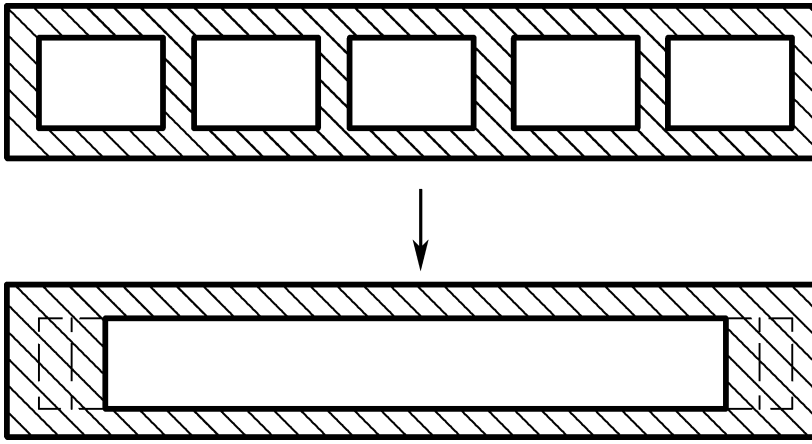

Figure 7.6. Top — stylized view of kiss-off structure of Figure 7.4 Bottom — schematic for moment of inertia

The moment of inertia for a ribbed structure is then given as:

$$I_{NA} = [bw^3/12] + bw[(h - w/2) - y_c]^2 + [nw(h - 3w/2)^3/12] + naw[(h - 3w/2)/2 - y_c]^2 + [nw(w/2)^3/12] + naw[w/2 - y_c]^2 + [nw(h - w)^3/12] + 2nw(h - w)[(h - w)/2 - y_c]^2 \quad (7.18)$$

As before, the first two terms on the right represent the contribution of the top plate. The next two terms represent the contribution of the kiss-off that touches the top plate. The third set of two terms represents the contribution of the bottom plate and the fourth set of terms represents the vertical sides of the kiss-offs. As before, the stiffness of a hollow panel S_{HP} with kiss-offs is given as:

$$S_{HP} = EI_{NA} \quad (7.19)$$

where I_{NA} is given by the equation above. Whenever hollowed-out or foamed structures are compared with compact structures, the comparison should be as stiffness-to-weight ratio. Typically, hollowed-out and foamed structures achieve substantial weight savings over solid structures but exhibit increased load deflection.[11]

7.3.6 *Creep*

When polymers are under load for long times, they distort in a time-dependent way. This is known as creep and is manifested as an increase in strain level in the polymer. As noted earlier, the initial slope of the polymer stress-strain

curve is the modulus, E:

$$E(\theta,T) = \sigma/\varepsilon(\theta,T) \tag{7.20}$$

where σ is the applied stress, ε is the resulting strain and θ is time. Figure 7.7 shows time-dependent strains for three polymers subjected to 6.9 MPa (1000 lb/in^2) tensile stress.[12] Even though polybutylene has the highest initial strain, it does not creep to the extent that PP and PE do. It is common practice to write a time- and temperature-dependent creep modulus as:

$$E(\theta,T) = E_0(T)\, e^{-\beta\theta} \tag{7.21}$$

where β is the slope of the time-log strain curve. Creep is detailed extensively elsewhere.[13–16]

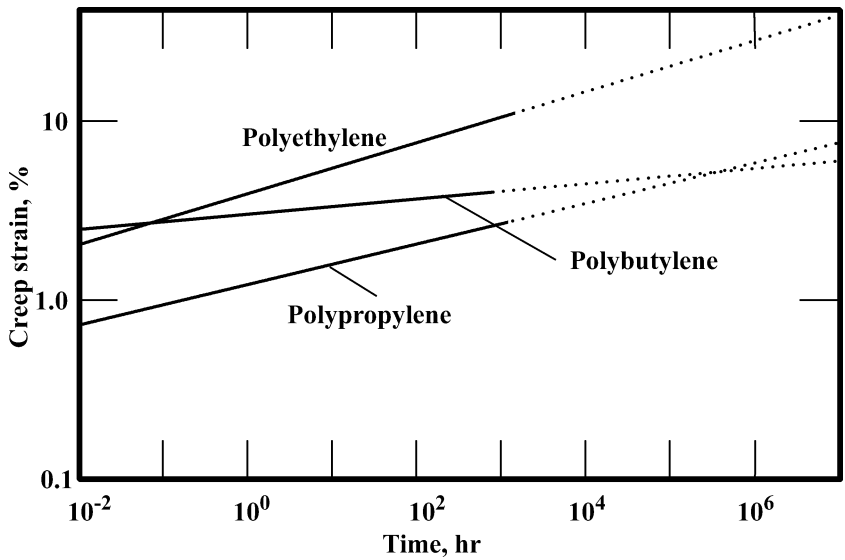

Figure 7.7 Tensile creep strain at 6.9 MPa (1000 lb/in^2) tensile stress,[12] redrawn, used with permission of Hanser Verlag, Munich

7.3.7 *Temperature-Dependent Properties*

An empirical equation, known as the Williams-Landel-Ferry or WLF equation, is used to determine polymer properties at temperatures other than those

given in standard sources. A shift factor, a_T, is used for polymers:

$$\log_{10} a_T = \frac{-C_1(T - T_0)}{C_2 + T - T_0} \tag{7.22}$$

where C_1 and C_2 are polymer-related constants and T_0 is a reference temperature. T_0 is frequently just the glass transition temperature of the polymer. Table 7.1 gives values for some rotationally molded polymers:

Table 7.1 WLF Constants for Rotationally Molded Polymers

Polymer	C_1	C_2	T_0(°C)
Polyethylene	17.4	51.6	-100
Polypropylene	17.4	51.6	-10
Polycarbonate	16.14	56	150
Polystyrene	14.5	50.5	100
Nylon 6	17.4	51.5	50
Universal constant	17.44	51.6	(T_g)

For modulus, for example, the shift factor, a_T, is used as:

$$E(\theta, T_2) = E(\theta / a_T, T_1) \tag{7.23}$$

If $T_2 > T_1$, $\log_{10} a_T$ is negative, $a_T < 1$ and $E(T_2) < E(T_1)$.

7.4 Design Properties of Foams

As noted in Chapter 6, there are two types of foam structures produced in rotational molding. The uniform density or single layer foam products do not have quality surfaces and so are used for dunnage or flotation. The multilayer foam structure is desired where one or both surfaces must be appearance surface, as with equipment cabinets and doors.

7.4.1 *Uniform Density Foams*

As noted in the section above, the stiffness of a structure, S, is the product of the modulus of the polymeric material, E, and the moment of inertia, I, of the structure:

$$S = EI \tag{7.2}$$

For unfoamed polymers, E is simply the polymeric modulus, obtained from handbooks or from the initial slope of the stress-strain curve. The moment of inertia is defined by the geometry of the structure. The modulus of uniform density foam is proportional to the extent of foaming according to:[17]

$$E_f/E_0 = (\rho_f/\rho_0)^2 \tag{7.24}$$

where E_f is the modulus of the foam, E_0 is the modulus of the unfoamed polymer, ρ_f is the density of the foam and ρ_0 is the density of the unfoamed polymer. Note that if the part is foamed 30%, the modulus is reduced by about 50%.

For a simple beam in flexure, the moment of inertia is given as:

$$I = bh^3/12 \tag{7.1}$$

where b is the width of the beam under load, and h is the thickness of the beam. Consider now two scenarios that help to explain the rationale behind foaming:

- If the polymer is foamed 30% and wall thickness is unchanged from the unfoamed part to the foamed part, the part weight is reduced by 30% (Figure 7.8, Left). The modulus is reduced by 50% but the moment of inertia remains the same and hence stiffness is reduced by 50%.
- If the part is foamed 30% and the part weight is kept unchanged (Figure 7.8, Right), the wall thickness increases 1/0.7 or 43%. The moment of inertia increases $(1.43)^3$ or 2.92 times. Even though the modulus is reduced by 50%, the stiffness is $0.5 \times 2.92 = 1.46$ times that of the unfoamed part.

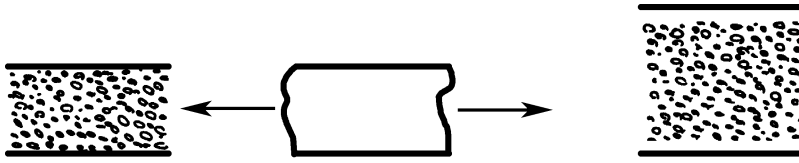

Figure 7.8 Uniform density foaming

Wall stiffness can go through a maximum, depending on the general foaming efficiency, as seen in the last column of Table 7.2. When the structure has

Table 7.2 Effect of Dosage of Azodicarbonamide (AZ) on Foaming Characteristics of MDPE (Table 6.16, Repeated, With Calculated Stiffness Added)

CAB Level (% wt)	Wall Thickness (mm)	Density (kg/m^3)	Density Reduction (%)	Wall Thickness Increase (%)	Relative Stiffness (%)
None	3.5	931	None	None	100
0.2	6.0	639	32	42	132
0.5	7.8	451	52	56	88
0.8	10.8	373	60	68	76
1.0	13.0	310	68	73	53

been loaded beyond the point where the neutral axis is no longer within the wall of the part, foam strength must be considered. Foam strength appears to decrease in proportion to the density to the 3/2-power:

$$T_f/T_0 = (\rho_f/\rho_0)^{3/2} \tag{7.25}$$

where T_f is the tensile strength of the foam, T_0 is that of the unfoamed polymer, and the density ratios are the same as earlier. This equation appears to satisfy yield strength, as well.[18] Impact strength is strongly dependent on the general impact resistance of the unfoamed polymer, the rate of impact, the shape of the part, the cell size, and the localized stress concentration at the point of impact.[19] The following general observations can be made:

- If the unfoamed polymer is brittle at impact conditions, foaming may make it more brittle.* For all intents, the nature of the impact failure will remain about the same. PMMA acrylic is an example of this.
- If the unfoamed polymer is brittle when notched but ductile when unnotched, foaming will embrittle it. Thus, the foamed polymer may be brittle, whether notched or unnotched. Polycarbonate and PP homopolymer are examples of this.
- If the unfoamed polymer is ductile for all tests, foaming may embrittle it to the point where it may be brittle when notched but ductile when unnotched. Or the foamed polymer may appear brittle under flexed-beam impact testing but may appear ductile under flexed-plate impact testing. HDPE, PVC plastisol, and PP copolymer are examples of this.
- For certain polymers, foaming does not appear to induce great changes in polymer ductility. LDPE, EVA, and certain TPEs are examples.

Figure 7.9 gives a guide to the relationship between brittle stress and yield stress of several rotational molding polymers.[20] One empirical equation yields some information about the influence of foaming on impact strength:

$$I_f/I_0 = (\rho_f/\rho_0)^m \times (h_f/h_0)^n \tag{7.26}$$

where I_f is the impact strength of the foam, I_0 is that of the unfoamed polymer, the density ratio is as given earlier, and h_f and h_0 are the thicknesses of foamed

* Some technologists believe that brittleness is an absolute lower value. When something is brittle, changes to it cannot necessarily make it *more* brittle.

and unfoamed polymer, respectively. Some values of *m* and *n* are given in Table 7.3.

Table 7.3 Parametric Values for Selected Foams

Polymer	*m*	*n*
Polystyrene	4	2 to 3
MPPO	4	3
Polyurethane RIM	4	2 to 3
HDPE	3 to 4	2 to 3
PP	3	1

It must be understood that impact values for high-density foam always show broad scatter.[21]

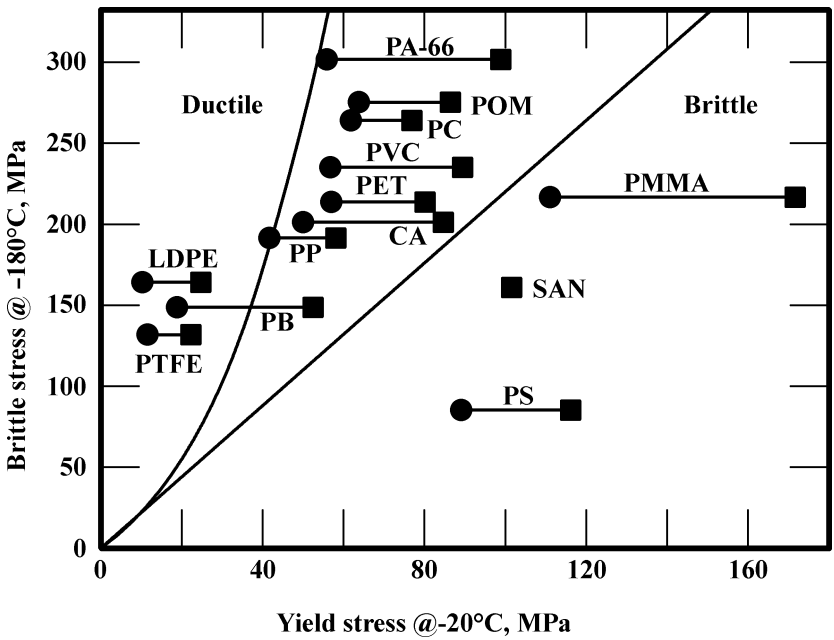

Figure 7.9 Comparison of brittle stress and yield stress of many rotationally molded polymers. Polymers left of envelope are inherently ductile, polymers right of envelope are inherently brittle, polymers within the envelope are notch-sensitive brittle, redrawn, used with permission of copyright owner

7.4.2 *Multilayer or Skin-Core Foams*

The classical structure envisaged for multilayer foams is called the "I-Beam" structure (Figure 7.10). The stiffness equation cited earlier is still used, but the width of the foam core is reduced in proportion to the ratio of foam core to skin moduli. If the overall skin thickness, d, is defined in terms of the total thickness of the foam, h, as $e = d/h$, the effective I-beam foam stiffness is given as:*

$$S = E_0(bh^3/12)\ \{[1 - (1 - 2e)^3] + (\rho_f/\rho_0)^2(1 - 2e)^3\} \tag{7.27}$$

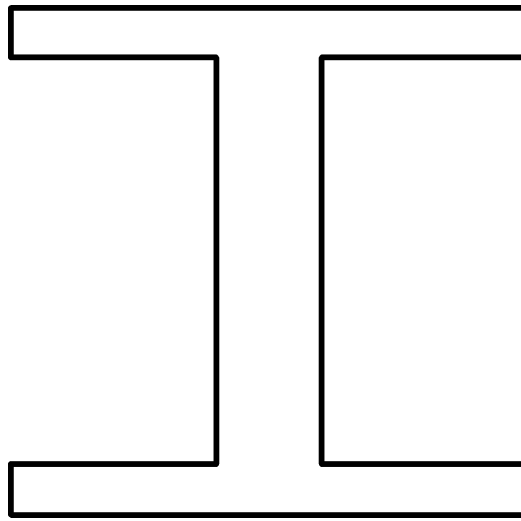

Figure 7.10 Characteristic I-beam depiction for foams with discrete skins

Note that the first part of the expression on the right is simply the stiffness of the unfoamed polymer:

$$S_0 = E_0(bh^3/12) \tag{7.28}$$

Therefore the expression in the braces represents the relative effect of foam on the stiffness. If $e = 1/2$, there is no foam core, the term in the braces is unity, and the stiffness is correctly that of the unfoamed polymer. If, on the other hand, $e = 0$, there is no skin, the term in the braces is the square of the

* This equation assumes that the skin has the same thickness on both sides of the foam core. A similar equation can be derived for skins of different thickness or for a structure with only one skin.

reduced density, and the stiffness is that of a uniform density foam. It is apparent in Figure 7.11 that the skin acts to stiffen the foam structure.

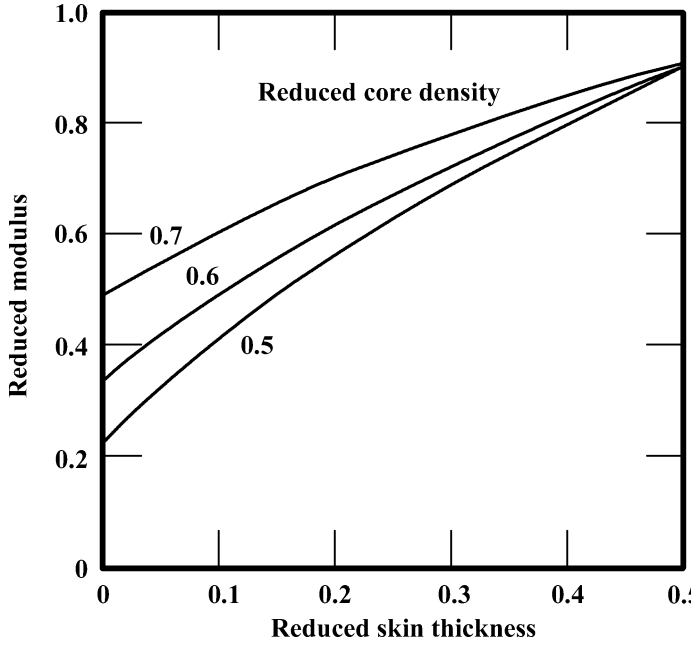

Figure 7.11 The effect of skin thickness on reduced modulus for skin-core or I-beam structured foams, redrawn, used with permission of copyright owner

Although this equation is designed for structures where there is a distinct interface between the skin and the core, it can be used for structures where there is a gradual density gradient from the surface to the center of the wall. However, arithmetic for the so-called "polynomial beam" structure (Figure 7.12) yields much more accurate stiffness results.[22]

7.5 Computer-Aided Engineering in Rotational Molding

As with all technical processes and products today, computers are used extensively in rotational molding. Figure 7.13[23] illustrates some of the areas where computers are used, beginning with solid modeling of designer's concepts, continuing through computer-aided mold design, process control, mechanical design and performance prediction, and ending in quality control. Some of these areas are discussed below.

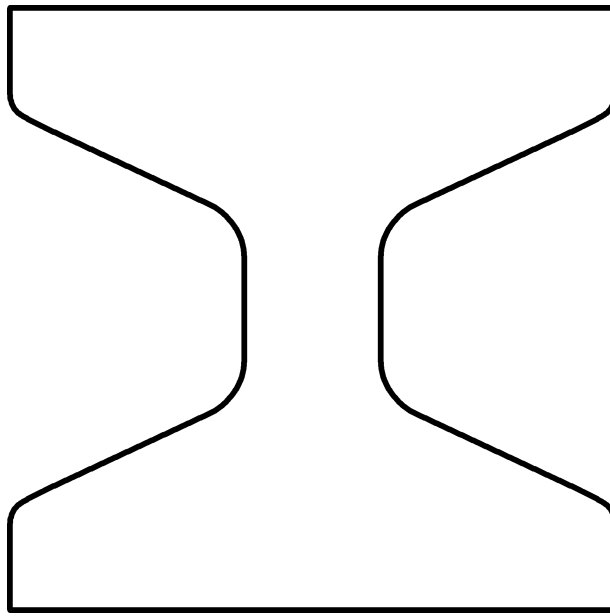

Figure 7.12 Characteristic polynomial beam depiction for foams with indistinct skins[20]

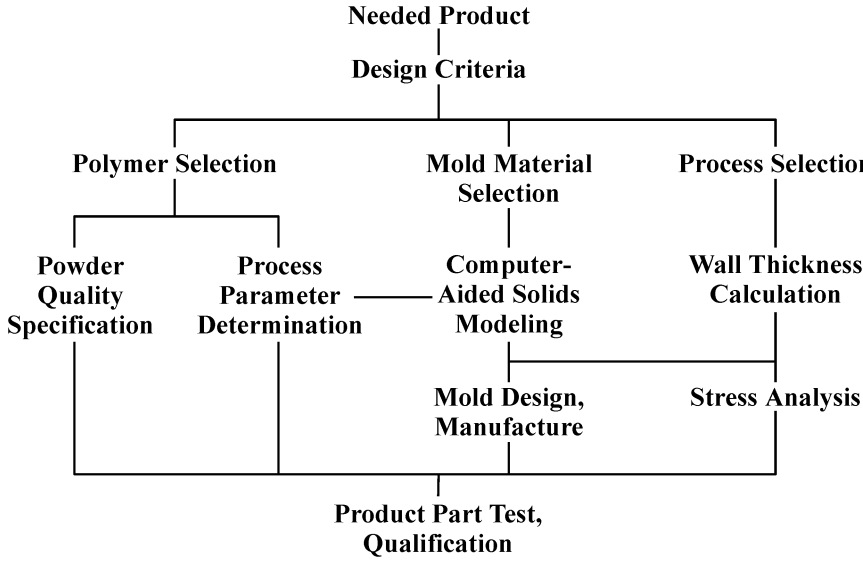

Figure 7.13 Computer-aided engineering in rotational molding,[23] redrawn, used with permission of copyright owner

7.5.1 *CAD/CAM in Rotational Molding*

Computer-aided design and computer-aided manufacturing or machining are used extensively in polymer manufacturing. Computer-aided design ranges from two-dimensional software-driven drafting formats to three-dimensional programs that allow wire designs to be rotated and cut through and solid surfaced designs to display various textures, colors, and decorations.[24] These computer programs allow the designer to quickly evaluate appearance and fit of component pieces, if necessary. Most CAD/CAM packages work in Data eXchange Format or DXF, although many have the capability of producing files in Initial Graphics Exchange Specification or IGES and PATRAN formats. As noted below, file incompatibility is the designers' most vexing problem.

Programs such as AutoCAD, Pro-Engineer, Iron CAD, SolidWorks, and CADKey provide for rapid updating of all line drawings. Furthermore, the designer can include expected shrinkage factors. For many parts, a pattern is needed. There are two general types of computer program-driven technologies that are used to produce a pattern. Deductive technologies rely on computer-driven machining stations to extract the desired shape from a block of machinable material such as aluminum, polymeric foam, or wood. Adductive technologies rely on program-driven rapid prototyping methods, such as Laminated Oriented Material (LOM), which creates the pattern by cutting paper or Stereolithography (SLA), where a resin is reacted in a computer-controlled fashion.[25,26]

Although most rotational molds are manufactured in cast aluminum, there is a growing interest in machined aluminum, particularly for smaller molds. Machined aluminum molds can be manufactured directly from three-dimensional computer software using Computer Numerically Controlled (CNC) driven three-axis workstations. There is also growing interest in finishing cast aluminum molds on CNC machines. Computer-driven multi-axis machines are also being used in trimming and drilling finished molded parts. This is discussed below.

7.5.2 *Computer-Aided Stress Analysis*

The arithmetic given earlier for mechanical design of parts is for very simple shapes under simple static loads. More complex mathematical models are required when shapes and/or loads are complex or where loads are dynamic, transient, or periodic. To solve these problems, extensive computer-driven

analyses have been developed over the last two decades or so. There are two general approaches.

The first focuses on a mathematical definition of time- and temperature-dependent structural response to applied load. The analytical equations are then replaced with approximate equations that are then solved computationally.[27] This approach usually depends on the ability to accurately mathematically define the shape of the part and on well-defined material equations, called constitutive equations. Usually the complexity of most molded parts prevents exact mathematical definitions. As a result, the computational solutions are frequently compromises of real structural response. The general approach is the parsing of complex partial differential equations into a set of relatively simple first-order one-dimensional equations that are solved simultaneously. One way of writing this is:

$$\begin{aligned} dX_1/d\theta &= f_1(X_1, X_2, \ldots, X_N) \\ dX_2/d\theta &= f_2(X_1, X_2, \ldots, X_N) \\ &\cdots \\ dX_N/d\theta &= f_N(X_1, X_2, \ldots, X_N) \end{aligned} \tag{7.29}$$

The protocol assumes that each independent variable value at time $\theta + d\theta$ is determined from the functional values calculated at time θ. Owing to error generation and growth, this simple stepping-forward method is inadequate for all but the most stable equations. As a result, there is an extensive collection of prediction-correction or adaptive methods available to achieve global convergence and minimize solution inaccuracies. One computational approach that usually yields expected results is the computational solution of transient heat transfer using finite difference equations or FDEs.[28]

A more versatile mathematical technique is finite element analysis (FEA). FEA was originally developed in civil engineering to analyze complex bridge loading.[29,30] Early models focused on temperature-independent Hookean-elastic structures under static loads. FEA is now capable of solving extremely complex, temperature-dependent, dynamically loaded structures with very complex stress-strain-rate of strain constitutive equations of state.[31] The philosophy of FEA is diametrically opposite that of analytical methods and FDE. The traditional methods assume that the structure is a global continuum that is described wholly by mathematical equations. FEA replaces the structure with a countable number of finite-sized elements. These elements are then usually described by a set of algebraic equations that are linked through the boundaries

of the elements. These equations are then simultaneously solved primarily through matrix inversion of the algebraic coefficients. The elements are "finite elements" and the interconnections between the elements are the "nodes." The method of replacing the continuum with the interconnected set of elements is known as "discretization." The approach, as a whole, is called Finite Element Analysis (FEA). The general approach is given in Table 7.4.

Table 7.4 FEA Formalization (Adapted from Ref. 31)

- Divide or "descretize" structure into finite elements
  Typically, for thin structures, the elements are two-dimensional. Element shape depends on the computer software, usually the shape is hexagonal, rectangular or more typically, triangular.
- Identify the element properties
- Create the stiffness matrix for each element
  The matrix relates the nodal displacements to applied forces, using some mathematical model.
- Apply the load
- Define the boundary conditions
  Care must be taken here to ensure that the boundary conditions are identified everywhere. Inappropriate or missing boundary conditions rapidly lead to error generation and instability.
- Solve the equations
  The classic method of solution of the set of linear algebraic equations is matrix inversion, where the nodal displacements are the unknowns.
- Display the resulting stresses
  The commercial software programs typically present the solution in graphical form and frequently use false color display to illustrate stress fields. Usually white or light yellow is used to show highest stress and black or deep violet to show lowest stress.

The general FEA arithmetic deals with an n-dimensional set of force-response equations that are written symbolically as:

$$[K]\ \{a\} = \{F\} \tag{7.30}$$

where $[K] = K_{ij}$ $(i,j = 1, 2,...n)$ are related to the partial derivative terms in the

functional equations, $\{a\} = a_i$ $(i = 1, 2,...n)$ are the unknowns, and $\{F\} = F_j$ $(j = 1, 2,...n)$ are the forcing functions.[32] The solution to this equation is:

$$\{a\} = \{F\}\ [K]^{-1} \tag{7.31}$$

where $[K]^{-1}$ is the inverted matrix of $[K]$. Inversion of matrices of thousands of elements requires substantial computational time. Furthermore, in most FEA problems, this matrix inversion must be accomplished thousands of times. However, $[K]$ is usually a narrow-banded sparse matrix. As a result, special algorithms allow rapid inversion, and as a result, FEA problems containing thousands of elements can be solved in relatively rapid fashion.

Very early FEA programs required very large, high-speed computers. Programs for workstations were either compromised in accuracy or required substantial computer processing units (CPUs). As a result, programmers used relatively coarse meshes of a few hundred elements. Very frequently, solutions needed to be iterated to improve accuracy in higher stress areas. This was done by selecting finer meshes in higher stress areas. As a result, overall computational efficiency was not great. Two aspects of computer technology have improved this situation. First, personal computers (PCs) continue to increase in computational speed and memory capacity. And as noted above, software manufacturers have developed algorithms to enhance computational speed without sacrificing accuracy or increasing error generation levels. As a result, very sophisticated FEA structural analysis programs having tens of thousands of elements and complex time- and temperature-dependent stress fields can be solved in minutes to a few hours on very inexpensive PCs.

Most FEA packages use Initial Graphics Exchange Specification (IGES) format and many CAD/CAM design packages do not yield compatible files. Not only is compatibility from CAD/CAM-to-FEA important, but the reverse is also important. For example, if the FEA program finds an undesirable weak spot in the design, the designer needs to have the computer capability of redesigning the CAD/CAM program to accommodate necessary changes. At the present time, the major time bottleneck remains the general incompatibility with programs that describe the geometry of the physical part.[33]

7.6 Some General Design Considerations

The design of rotationally molded products requires a working relationship between aesthetics and performance. Rotational molding offers the designer

a unique way of manufacturing "bulky" articles from simple balls to complex near-parallel walled structures. Since very little pressure and shear are applied during processing, products are essentially stress-free. And as noted earlier, the way in which powder is distributed and coalesced on the mold surface yields an inherently nearly uniform wall thickness.

There are certain guidelines that the designer of rotationally molded products should keep in mind, however. This section reviews some of those that are intrinsically connected to the technical aspects of the process itself. The reader is directed to a very recent design analysis book by Beall for a more in-depth analysis of the design aspects of rotational molding.[34]

7.6.1 *Uniformity in Wall Thickness*

Even though rotational molding yields inherently uniform walls when compared with thermoforming and blow molding, rotational molding is a single-surface process similar to thermoforming and blow molding. As a result, wall thickness *tolerance* is never as good as two-surface processes such as extrusion and injection molding. For generic, run-of-the-mill parts such as tanks and outdoor toys, rotationally molded part wall thickness tolerance is ±20%. For certain tight tolerance products such as medical face masks and optical parts, a tolerance of ±10% can be specified, albeit with a greater percentage of rejects.* As a result of this wide tolerance, in rotational molding, as well as blow molding and thermoforming, it is common to specify *minimum* wall thickness rather than *nominal* wall thickness.**

The primary objective in any part design is to make the product capable of withstanding expected loads with appropriate safety factors, but without adding so much polymer that the product is no longer economically competitive. Table 7.5 shows approximate wall thickness ranges for many rotationally molded polymers.

Final part wall thickness uniformity is the result of the early processing step of tackifying. This stage is an averaging step in the process. Once the powder begins adhering to the mold surface, slip flow disappears. Although steady bed circulation is possible, the amount of powder remaining in the

* One source[35] considers the general tolerance limits to be ±5%

** Instead of specifying a *nominal* wall thickness of, say, 6 mm, as is common with injection molding where the tolerance may be ±0.2 mm, the rotational molded *minimum* wall thickness would be 5.8 mm with a tolerance of –0 mm to +2.3 mm. If a *nominal* wall thickness must be specified for this rotationally molded part, it would be 7 mm ±1.2 mm.

static bed is rapidly decreasing, and the most probable powder behavior is avalanche flow.

Table 7.5 Wall Thickness Range for Rotationally Molded Polymers

Polymer	Minimum Wall Thickness (mm)	Typical Wall Thickness Range (mm)	Maximum Wall Thickness (mm)
LLDPE	0.5	1.5 – 25	75
HDPE	0.75	1.5 – 25	50
FPVC	0.2	1.5 – 10	10
Nylon 6	1.5	2.5 – 20	40
PC	1.25	1.5 – 10	10
EVA	0.5	1.5 – 20	20
PP	0.5	1.5 – 25	25

The keys to uniform powder laydown on the mold surface are the uniformity in residence time of the static powder bed against every part of the mold surface and the uniformity of the mold surface temperature on every part of the surface. The first is controlled by the rates of rotation of the major and minor axes. It is apparent that if powder does not contact a portion of the mold surface, it cannot adhere to it. Furthermore, if the powder accumulates or packs against a portion of the mold surface, the final part wall in that region will be thicker than that elsewhere on the part. The second is dependent on the uniformity of heat transfer to the mold and uniformity of the mold thickness everywhere. If hot air cannot circulate freely into deep cavities, or the mold is shielded from the circulating hot air, or if the mold wall is unusually thick in a given area, powder will not stick and fuse to the inner mold surface as quickly as elsewhere. The result will be that the final part wall in that region will be thinner than that elsewhere on the part.

7.6.2 *Shrinkage During Cooling*

All polymers exhibit volumetric shrinkage when cooling from the liquid state to room temperature. Crystalline polymers such as polyethylene, polypropylene, and nylon exhibit up to five times the shrinkage of amorphous polymers such as polycarbonate. Figures 7.14 and 7.15 show typical temperature-dependent specific volume curves, known as P-V-T curves, for high-density

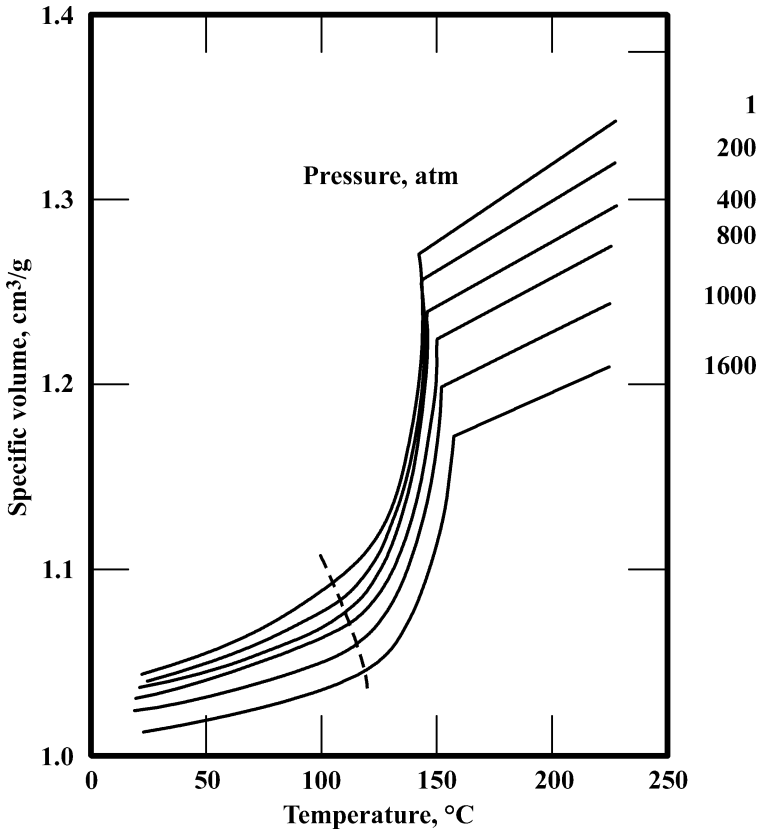

Figure 7.14 Temperature-dependent specific volume curves for HDPE,[36] redrawn, used with permission of Hanser Verlag, Munich. Rotational molding is concerned only with the 1-atm pressure curve

polyethylene and polycarbonate, respectively.[36] If the polymer is unconstrained or allowed to shrink without restriction, shrinkage is uniform in all directions. Linear shrinkage, S_L, is given in terms of volumetric shrinkage, S_V, as:

$$S_L = 1 - (1 - S_V)^{1/3} \tag{7.32}$$

This expression is simplified to:

$$S_L = S_V/3 \tag{7.33}$$

for small amounts of volumetric shrinkage. In traditional rotational molding, the polymer is isotropic and unconstrained, for the most part. As a result, the

molded part shrinks essentially uniformly in surface area and thickness. The exception is when the part is constrained by mold design. Male portions of the mold, such as ribs, bosses, and gussets tend to restrict polymer shrinkage. Differential shrinkage between unconstrained and constrained portions of the part is a leading cause of warpage and part distortion.

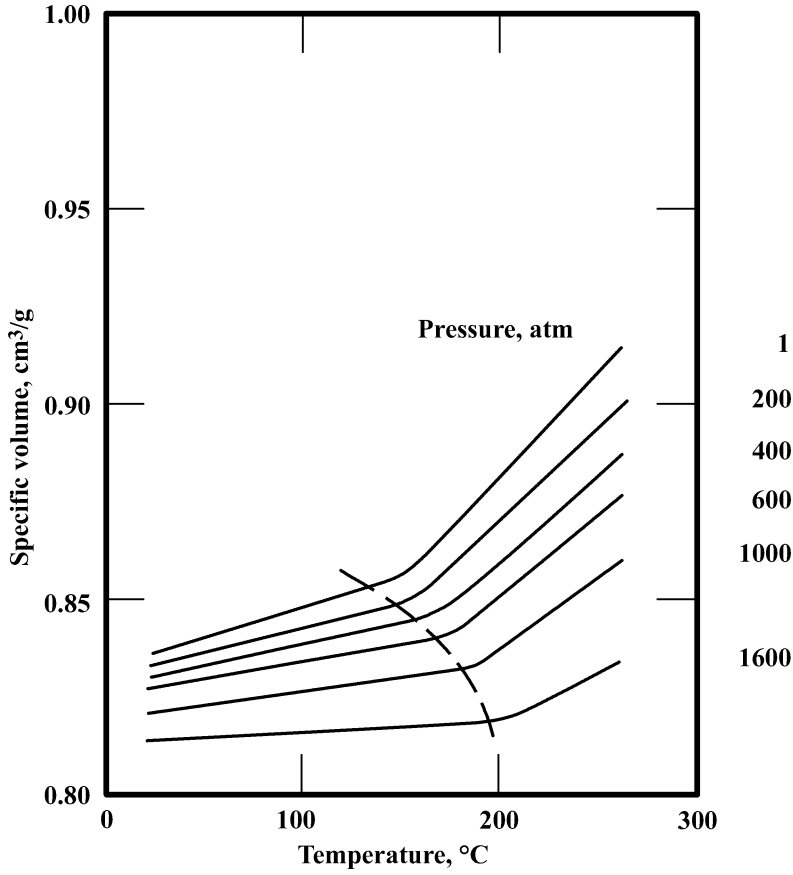

Figure 7.15 Temperature-dependent specific volume curves for polycarbonate,[36] redrawn, used with permission of Hanser Verlag, Munich. Rotational molding is concerned only with the 1-atm pressure curve

7.6.3 *General Shrinkage Guidelines*

Plastics increase in density and therefore decrease in volume as they cool.

Table 7.6 gives typical linear shrinkage values for the major rotationally molded polymers.*

Table 7.6 Linear Shrinkage Values for Rotationally Molded Polymers[37]

Polymer	Shrinkage Range (%)	Recommended (%)
LDPE	1.6 – 3.0	3.0
HDPE	3.0 – 3.5	3.5
PP	1.5 – 2.2	2.2
FPVC*	0.8 – 2.5	1.5
PC	0.6 – 0.8	0.8
CAB	0.2 – 0.5	0.5
Nylon 6	1.5 – 3.0	3.0

* This high value attributed to plasticized PVC is thought to be due to consolidation and dissolution of adducts into the free volume of the polymer superstructure during processing and therefore this is not a true shrinkage.

Typically, amorphous polymers such as PC and styrenics exhibit shrinkage values on the order of 0.4% or so, whereas crystalline polymers such as PEs exhibit shrinkage values on the order of 3%. The greater the final crystallinity of the polymer becomes, the greater will be the degree of shrinkage. And the greater the degree of shrinkage, the easier it is to remove a part from a female mold cavity.** For highly crystalline polymers such as PTFE and in certain cases, HDPE, parts can be produced with zero draft angles on male surfaces. It is also noted[38] that parts are much easier to remove from low-draft angle molds if the part is flexible or pliable at the time of demolding, due to the nature of the polymer, the part temperature, or the thinness of the part wall. Typically, thin-walled FPVC, LLDPE, EVA, and LDPE parts can be readily pulled from low-draft angle molds. HDPE, CAB, and PC are very difficult to remove.

7.6.4 *Effect of Pressurization*

Pressurization seems to be more effective with slowly crystallizing polymers such as nylon and polypropylene, with the pressure maintained until the part temperature is substantially below the polymer recrystallizing temperature.

* Also, read the description of shrinkage during cooling in Chapter 6.

** But the more difficult it is to retain uniform heat removal during cooling, as highly crystalline parts tend to shrink away from the male mold cavity surface. This subject, along with the subjects of differential shrinkage and warpage, was discussed in Chapter 6.

For close tolerance parts, the room temperature part is sometimes placed in a fixture and held under pressure for several hours to ensure dimensional control. In difficult cases, the part may be held at elevated temperature while fixtured and pressurized.

When the polymer pulls away from the mold, the effectiveness of conduction heat removal from the part substantially decreases. Air has an effective thermal conductivity of about 10% that of the polymer. The resistance to heat removal can be considered as a series of resistances:

$$Q = \frac{\Delta T_{\text{mold}}}{L_{\text{mold}}/K_{\text{mold}}} + \frac{\Delta T_{\text{air}}}{\Delta x_{\text{air}}/K_{\text{air}}} + \frac{\Delta T_{\text{polymer}}}{L_{\text{polymer}}/K_{\text{polymer}}} \tag{7.34}$$

It is apparent that as the air gap dimension increases, the effective rate of heat removal decreases. In one parametric study, an air gap of 0.0100-inch or 0.25 mm reduced the rate of heat removal by a factor of two.[39] Experimentally, the effect is seen as a slowing of the rate of cooling of the air inside the molded part.

In actuality, there are two effects that cause the decrease in the cooling rate of the air inside the part — the liberation of energy during recrystallization, and shrinkage, resulting in the formation of the air gap. Since both are the result of polymer morphology, they occur at about the same time and temperature. And, typically, the higher the level of crystallinity, the greater the amount of energy that is liberated and the greater the volumetric shrinkage is. Thus, although it makes sense to pressurize the mold to minimize the heat transfer resistance through the air gap, experimentally it is difficult to determine the absolute reduction in overall cooling time.

The primary justification for using pressure should then be measurably reduced part warpage and distortion, rather than improved cooling time.

7.6.5 *Draft Angles and Corner Angles*

Male mold elements, or mold elements that project into the inner mold cavity, present a different set of problems. Regardless of its morphology, cooling polymer will shrink onto a male portion of the mold. Certainly, the force required to strip the part from the male portion of the mold will increase as the polymer shrinkage increases. As a result, internal draft angles must be substantially greater for crystalline polymers such as olefins than for amorphous polymers such as CAB and PC. Table 7.7 is a guide to internal and external draft angles.

Table 7.7 Recommended Draft Angles for Rotationally Molded Polymers[40]

Polymer	Female or Outer Draft Angle (degree)	Male or Inner Draft Angle (degree)
LLDPE	0 to 1	1 to 2
HDPE	0 to 1.5	1 to 2.5
PP	0 to 1.5	1 to 2
EVA	0 to 1	1 to 2
FPVC	0 to 1.5	1 to 3
Nylon 6	1 to 2	1.5 to 3.5
PC	1.5 to 2.5	3 to 5
PBT	1 to 2	1.5 to 3

The values given in Table 7.6 assume a smooth mold surface. Obviously the greater the texture depth becomes, the greater the draft angle will need to be to get the part off a male or interior mold element.* One rotational molding guide recommends an additional 1 degree for each 0.001-inch (0.025 mm) of texture depth.[41] Although this additional allowance is mandatory for male mold elements, it is recommended that about half this additional allowance be incorporated in the draft angles for female mold elements, simply because texture represents microscopic undercuts against which the polymer can lock. Recommended draft angles for typical rotationally molded polymers against smooth and textured mold surfaces are in Table 7.8.

Table 7.8 Draft Angles for Smooth and Textured Molds[42] (Texture Depth is 0.1 mm)

Polymer	Smooth Mold (degree)		Textured (degree)	
	Female	Male	Female	Male
PE	1	2	3	6
FPVC	1.5	3	3.5	7
PC	2	4	4	8
Nylon 6	1.5	3	3.5	7
PBT	1.5	3	3.5	7

* Mold surface finish is discussed in detail in Chapter 5.

Keep in mind the dramatic effect draft angle has on part dimension. Consider the inner surface of a double-walled five-sided box nominally 1 meter on a side. As an example, if the inner mold surface is textured to the extent that the recommended draft angle is 7°, the side walls will taper inward to the extent that the bottom of the box will be only about 0.75 meters on a side.

In addition to the concern about draft angles on male projections, care must be taken when dealing with polymer shrinkage on corrugated structures.* As the polymer shrinks onto each of the male portions of the corrugation, the polymer between is also attempting to shrink, away from what appears to be the side walls of a female portion of the corrugation. The final shape of each corrugation depends strongly on the part wall thickness uniformity. If, as typical, the part wall is thin at the top or male portion of the corrugation and thick at the bottom or female portion of the corrugation, the part will lock onto the top of the corrugation and will pull away at the bottom (Figure 7.16). The resulting corrugation will be dished on the top and crowned on the bottom.

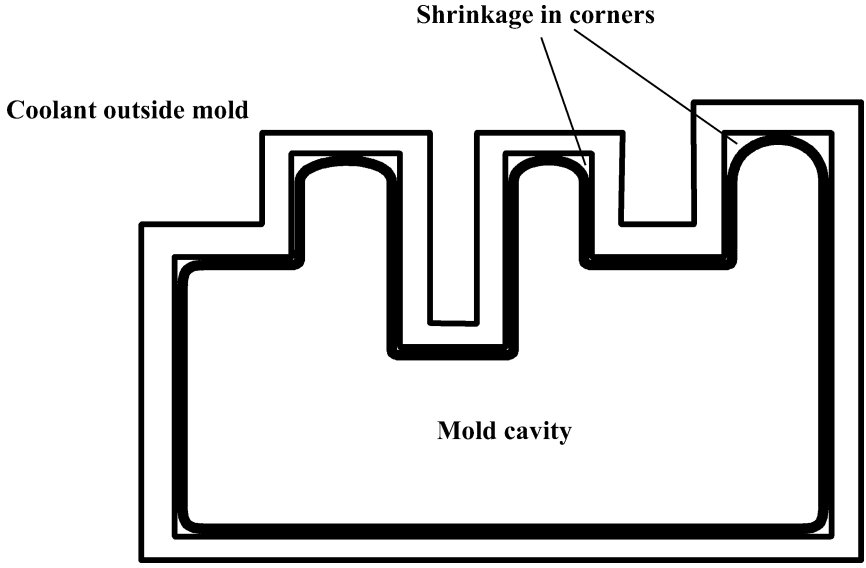

Figure 7.16 Schematic showing part shrinking away from inside corners and locking onto male portions of the mold

* Corrugations are used in place of ribs in single-sided processes such as rotational molding, thermoforming, and blow molding.

7.6.6 *Warpage Guidelines*

The more uniform the part wall thickness becomes, the more uniform the shrinkage becomes. However, even for products with very uniform wall thicknesses, warpage can result. Warpage is a measure of the nonuniformity of shrinkage. The problem is particularly critical for parts with large flat surfaces. The product ends are constrained by the mold corners while the centers of the flat surfaces pull away from the mold walls, causing a bowing or warpage. Table 7.9 gives industry-established standards for warpage of several polymers.

Table 7.9 Warpage Standards for Rotationally Molded Polymers (%)[42]

Polymer	Ideal	Commercial	Precision
Polyethylene	5.0	2.0	2.0
Nylon [PA]	1.0	0.5	0.3
Polypropylene	5.0	2.0	1.0
PVC Plastisol	5.0	2.0	1.0
Polycarbonate	1.0	0.5	0.3

While flat surfaces on plastic parts are appealing, they are difficult to achieve with any single-sided, low-pressure process such as blow molding, thermoforming, or rotational molding. The primary reason for this is apparent when one considers that polymers increase in density and decrease in volume as they cool from their forming temperature to environmental temperature. Polymers that crystallize exhibit greater volume change and higher shrinkage than amorphous polymers. Even though FPVC is amorphous, it also exhibits a high level of shrinkage. Differential cooling can pull the cooling polymer part away from the mold surface thereby exacerbating warpage.

A very smooth surface will accentuate distortion, whereas engraving, etching, texture, or ribbing can accommodate a certain degree of warpage or out-of-plane distortion. Typically, warpage is given as the extent of out-of-plane distortion per unit length of surface. For most commercial products, warpage tolerance should be ±2% for polyolefins and FPVC and ±0.5% for PC and nylons. For precision parts requiring very flat surfaces, warpage tolerance should be ±1% for polyolefins and FPVC and ±0.3% for PC and nylons. These precision tolerances are achieved only with substantial care on part design and with internal cavity pressure during the cooling step.

7.6.7 *Corner Radii — The Michelin Man*

While not always true, rotational molding processors believe that all product designers want zero-radius, razor-sharp corners and absolutely flat surfaces. And also while not always true, product designers believe that all rotational molding processors want to manufacture parts that resemble beach balls, with no flat surfaces and "Michelin Man" radiuses. Reality is somewhere in between these extremes.

7.6.7.1 *Right-Angled Corners*

It is true that very sharp corners are very difficult to produce, simply because the powder does not flow well into small radii. In addition, conduction heat transfer into a two-dimensional corner is less efficient than that into a one-dimensional wall. As a result, mold wall corners tend to be cooler than other portions of the mold and powder tends to stick first to the other portions of the mold. The powder that does stick and coalesce in a corner may not densify to the same level as that on the rest of the mold. During cooling, heat removal from the two-dimensional corner is less efficient than that over the rest of the mold. Therefore, the polymer remains hotter longer. The differential temperature in the polymer part can exacerbate part distortion and warpage. And, of course, the part wall is usually thinner in the corners, thus affecting product performance. In other words, there are some very practical reasons for not using small-radiused corners in rotational molding.

Table 7.10 Guidelines for Inner and Outer Radii Dimensions for Selected Rotationally Molded Polymers

Polymer	Inside or Female Radius (mm)			Outside or Male Radius (mm)		
	Ideal	Commercial	Minimum	Ideal	Commercial	Minimum
PE	13	6	3	6	3	1.5
FPVC	9.5	6	3	6	3	2
Nylon 6	19	9.5	4.75	13	9.5	4.75
PC	13	9.5	3	19	9.5	6

In addition, most product designers are fully aware of the problem of stress concentration in small-radiused corners. Figure 7.17 shows a typical radius-dependent stress concentration curve.[43] Since mold design, mold material choice, method of mold manufacture, polymer type, particle size and size distribution, the presence of tails or fibers in the polymer powder, tack

and bridging characteristics of the polymer, and mold surface texture, all influence the local part wall thickness in corners, it is difficult to establish a guideline for minimum radii, other than stating the obvious, that all radii should be as large as possible. Nevertheless, the general guidelines in Table 7.10 are recommended.[44]

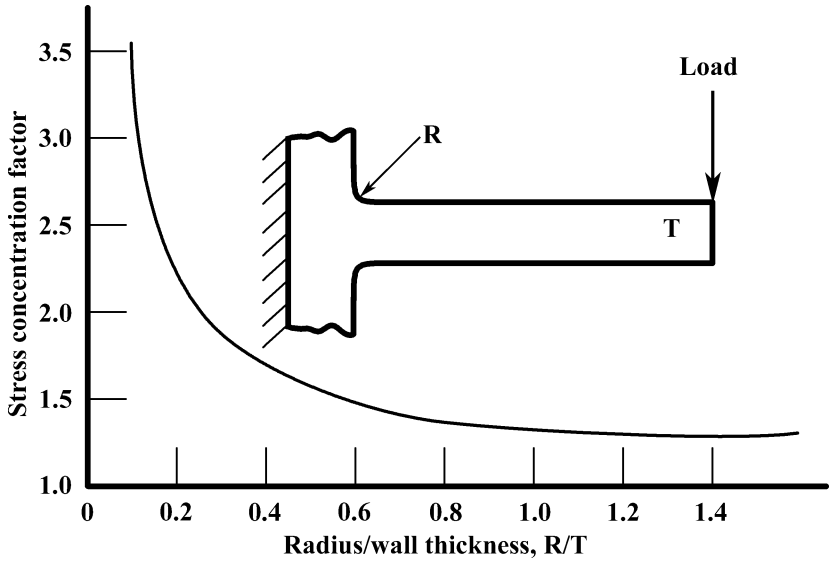

Figure 7.17 Stress concentration factor for cantilever beam, radius-to-thickness factor,[43] redrawn, used with permission of Hanser Verlag, Munich

7.6.7.2 *Acute-Angled Corners*

Not all parts have right-angled or 90-degree corners. Very acute angles are designed into some parts, such as the prow of a kayak. As is expected, the acute angle or narrowing flow channel can seriously compromise powder flow. Two opposing factors are at play. Powder may not freely flow into the channel and, once in there, powder may not freely flow out. As a result, acute-angled parts are frequently plagued with an effect called "bridging" (Figure 7.18). In effect, the sticky powder forms its own acute angle and only a small amount of powder ever gets into the corner. Acute angle filling is governed in general by the same processing characteristics as affect small radius filling, that is, mold design, mold material choice, method of mold manufacture, polymer type, particle size and size distribution, the presence of tails

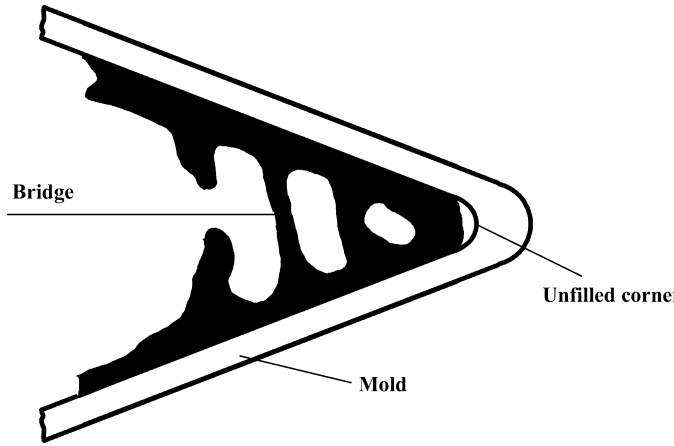

Figure 7.18 Bridging, voiding in acute-angled internal corners

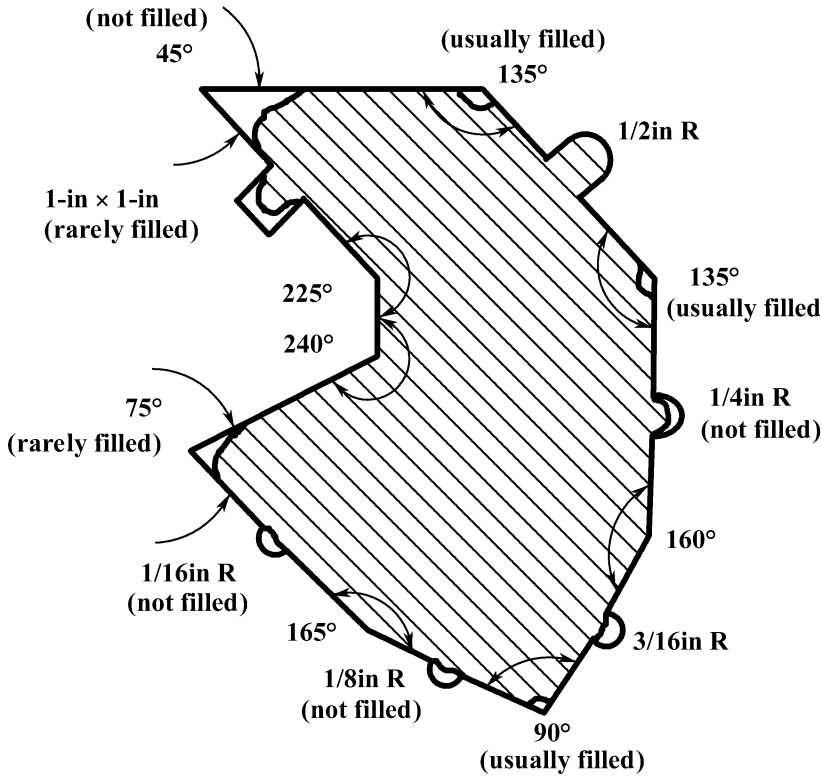

Figure 7.19 Mold configuration to test polymer powder flowability into corners, radii[45]

or fibers in the polymer powder, tack and bridging characteristics of the polymer, and mold surface texture. For most polymers, acute angles of 60° or more are acceptable. For PE and EVA, acute angles of 45° are routinely filled. With LDPE and highly plasticized FPVC, acute angles of 30° have been successfully filled. And acute angles of 20° have been filled using low-viscosity nylons. For a newer or unfamiliar polymer, it is recommended that a relatively simple corner mold (Figure 7.19) be used to evaluate the filling characteristics of the polymer.[45]

7.6.8 *Parallel Walls*

The rotational molding process is ideal for the manufacture of double-walled containers, particularly deep containers, such as insulated coolers, chests, and planters. Industrial blow molding and twin-sheet thermoforming are competitive processes but each has a limitation. Industrial blow molding is satisfactory for relatively flat doubled-walled shapes such as doors and exercise platforms but deep double-walled blow molded containers are technically difficult or impossible. While deep double-walled thermoformed containers are manufactured, the twin-sheet process leaves an inherent seam or weld line that may be aesthetically unacceptable. There are some practical restrictions to rotationally molded double-walled structures, however. For example, if the depth of the inside wall is greater than its opening, it may be necessary to actively force oven air into that portion of the mold in order to achieve mold wall temperature uniformity.[46] *

7.6.9 *Spacing and Bridging*

For parallel walls that represent only a small portion of the part, the two inside part walls can be spaced as close as three times the part wall thickness. For parallel walls that represent a large portion or most of the part, the distance between the two inside part walls should be at least five times the part wall thickness.** Keep in mind that for double-walled containers, the inner part surface is male and so must have greater draft than the outer part surface, which is female. As a result, the minimum distance between the two inside part walls, at the top edge of the container, should be greater than three times the part wall thickness. As noted in the discussion of acute angles, powder must flow freely across all mold surfaces and therefore, powder must flow

* Baffles can be used for relatively shallow cavities, but venturi devices are recommended if the depth-to-width dimension exceeds 0.5 or so. These devices are detailed in Chapter 5.

** Keep in mind that, for double-walled parts, there must be room for the powder in the molds.

freely between the parallel walls and into and out of the regions where these walls are joined. If the walls are too close, the powder may form a bridge at some point. This will restrict the amount of powder that can flow beyond the bridge. As a result, the final part wall thickness will be nonuniform. In addition, the bridge is usually thicker than the part wall and as a result, does not cool as quickly, leading to differential shrinkage and "sink marks" or depressions on both part wall surfaces.

7.6.10 *Internal Threads, External Threads, Inserts, and Holes*

Some of these elements were discussed in Chapter 5. Additional information can be found in Refs. 1, 41, and 47. The choice of method used to affix an element to a rotationally molded part depends strongly on the inherent strength of the polymer relative to the required design strength. For example, polyethylene, EVA, and plastisol PVC are soft plastics and threaded insert pullout strength is typically quite low. For HDPE, PP, nylon, and PC, very small diameter internal threads can be cut directly into the plastic wall after the part has been molded. Metal inserts, fastened to the mold wall prior to mold filling, are used when higher pullout strength is needed.

For larger diameter openings, both internal and external threads can be molded in. Typically, the thread surfaces must be rounded sufficiently to prevent localized bridging and void formation. If concentricity and sharp threads are required, the threaded section is manufactured as an insert either by injection molding or machining. In one scenario, the insert is fastened to the mold wall prior to mold filling, thus allowing the molten polymer to fuse to it during the rotational molding process. In another, the region on the rotationally molded part where the insert is to be placed is machined after molding, and the insert is either thermally welded or glued in place.

In many instances, an insert must pass through a sized hole in the part wall and must fit tightly on both sides of the part. A classic example is a grommet. An exactly dimensioned hole is achieved by drilling it, then locally machining the part wall to the appropriate thickness.

Most obviously, one way to achieve a very large opening is to rout or machine away the unwanted plastic after the part is removed from the mold. Another way is to heavily insulate the mold directly over the area where the opening is to be formed. Although some plastic may adhere to the mold, the wall will be much thinner than that over the rest of the part and trimming may be easily completed with a hand-held hook knife.

7.7 Process Effects on Porosity, Impact Strength

It is well-known by practitioners that optimum properties are achieved somewhere between the time when polymer porosity is gone or minimized and the time when the polymer thermally oxidizes. Typically, for polyethylene, the properties that normally peak and decline during the rotational molding process include:

- Impact resistance
  - Room temperature
  - Low temperature
- Tear resistance
- Outside surface appearance
- Outside surface color
- Melt index (MI)

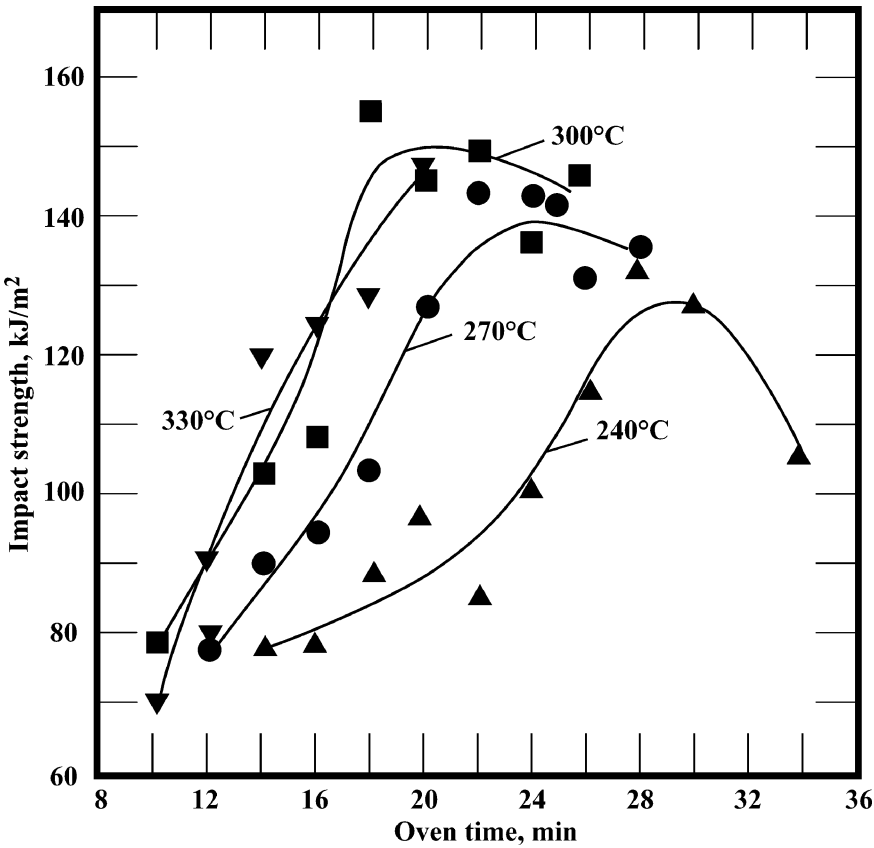

Figure 7.20 Effect of oven time and temperature on room temperature impact strength of Exxon Canada Sclair 8405 polyethylene.[50] Redrawn, used by permission of copyright holder

Table 7.11 Effect of Extent of Oven Time on Rotational Molding Polymer Characteristics (Adapted from Ref. 48).

Characteristic	Length of Oven Time						
	Very Short	**Short**	**Almost Right**	**Optimum**	**Slightly over Optimum**	**Longer than Needed**	**Excessive**
Odor	None	Little	Somewhat waxy	Waxy	Pungent	Very acrid	Burnt
Inside surface color	← Same as outside surface →				Slightly yellow	← Increasing to brown →	
Inside surface appearance	← Dull, matte →			← Shiny, glossy →			
Inside surface	Very rough texture	Rough	Waxy	Not sticky	Smooth, slightly sticky	Sticky	Very sticky
Inside bubbles	Very many	Many	Few to none	← None →		Few	Gross
Outside bubbles	Many	Few	Few to none	← None →		Few to many	Many
Fill	Bridging	← Some →		← Complete →			
Tear resistance	Poor	← Better →		← Maximum →			Decreasing

As expected, there are many parameters that influence the time range when polymer properties are optimum. Some of these include:

- Oven temperature
- Rate of heating
- Final part wall thickness
- Initial melt index
- Mold thermal resistance
- Inner cavity atmosphere
- Air
- Inert gas
- Oxidative resistance of polymer
- Nature of polymer adduct package

Table 7.11 shows one set of relationships between processing conditions and polymer characteristics.

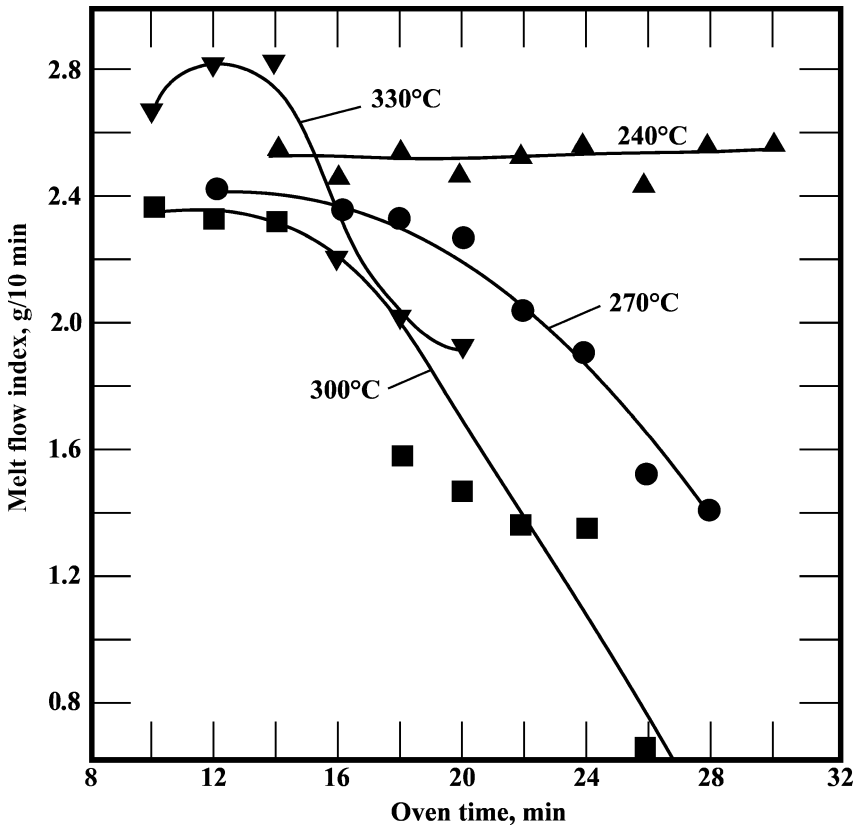

Figure 7.21 Effect of oven time and temperature on melt flow index of Exxon Canada Sclair 8405 polyethylene.[50] Redrawn, used by permission of copyright holder.

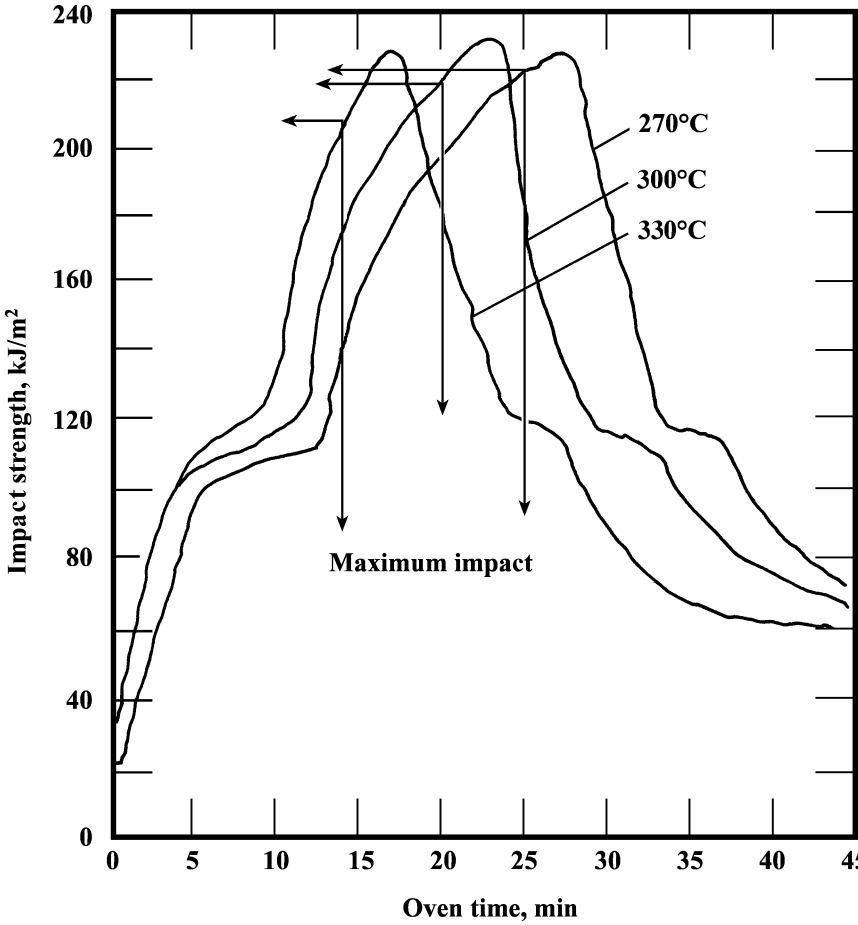

Figure 7.22 Impact strength correlated with actual mold cavity air temperature traces for three oven times. Redrawn, courtesy of Queen's University, Belfast.

As noted, many polymer properties go through maxima during coalescence, densification, and heating to final desired temperature. Figure 7.20 shows the effect of oven time and temperature on impact strength of polyethylene. Figure 7.21 shows the effect of oven time and temperature on melt index (MI)* of that same polyethylene.[49] As is apparent, the melt index, which is essentially an inverse measure of viscosity, decreases at excessive oven

* Keep in mind that *melt index* is a laboratory test wherein a sample of polyethylene is heated to 190ºC, then pressed through an orifice under a specific pressure. The reported melt index is the amount of polyethylene, in grams, extruded through the orifice in ten minutes.

time-temperatures. Characteristically, when polyethylene is heated for extended periods of time in an oxygen atmosphere, the resulting oxidative degradation yields crosslinking rather than chain scission. There has been substantial work recently in relating the peak of polyethylene impact strength with inner mold cavity air temperature,[50] (Figure 7.22).* Figure 7.23 shows similar results for mean impact failure energy for other polymers.[51]

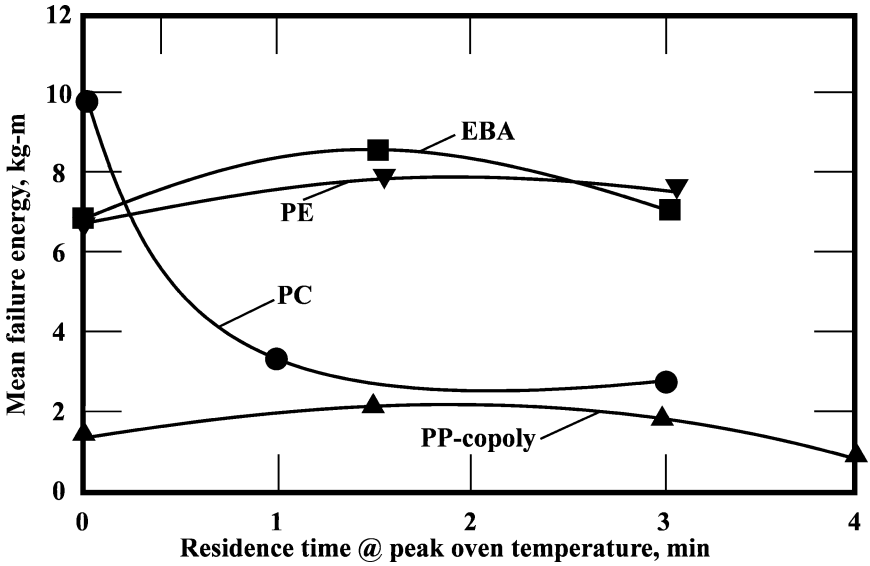

Figure 7.23 Effect of oven residence time on mean failure energy for four polymers.[51] EBA, PE, and PP-copolymer oven temperature at 310°C. PC oven temperature at 340°C. Used with permission of Society of Plastics Engineers, Inc.

7.8 Trimming

Until a few years ago, trimming of plastic parts was restricted to uniaxial trimming, using band saws or nonplanar trimming using hand-held routers. Multiaxis trimming was expensive and restricted to higher-performance products such as composites. In recent years, affordable computer-driven, large-bed multiaxis trimmers have been developed for trimming large size blow molding, thermoforming and, very recently, rotational molding parts. There are two types of accuracy that must be considered in automatic machining.

* Note in Figure 7.21 that the curves shown appear to be based on actual measured mold cavity air temperature plots rather than on actual measured impact strengths.

The first is accuracy of the machine to locate a particular computer-driven coordinate. The second is repeatability of the machine to move to a given machine coordinate every time. Typically, repeatability is about 10 times better than accuracy.[52] The question of accuracy in trimming is frequently intertwined with repeatability. Many items must be considered when discussing accuracy and repeatability.* For example, single-axis accuracy may be quite different than multiaxis accuracy. Then loaded repeatability must be compared with unloaded repeatability. Machine considerations such as lead screw backlash, rotary resolution of servomotor, encoder resolution and stepping interval, rail linearity, machine alignment, head alignment, particularly after crashes, and head worm spur gear tooth dimensional accuracy and backlash, must be included in any comparison.

Then secondary effects such as servo system tracking, inertial effects during acceleration and deceleration of the head, vibration, cutter push-off and flexing, cutter speed, tool length accuracy, and tool-to-collet tightening must be factored in. And the computer aspects of the trimming device, including CAD/CAM spline interpretation of curves and the actual trimming path on the part compared with the computer trim path, must be considered.

Then, the variability in overall part size needs to be considered when discussing cutter accuracy. This includes part temperature, raw material formulation and cooling characteristics, as well as polymer flexing under trim load, machine bridge flexing during carriage movement, dynamic machine flexing and bending at various cutter speeds, polymer reaction to cutter push-off, and the bending and flexing of the cutter tool under load. And when all these factors are understood, accuracy is also affected by thermal expansion and contraction in the router tool, in the polymer being trimmed, and in tool dimensional change during trimming. In addition, factors such as polymer warping and distortion during trimming, as well as trim direction when compared with any "grain" in the polymer, must be included. It has been concluded that *repeating* an accurate position in x-y-z space is far easier than *achieving* that accurate position in space.

Traditional three-axis machines, frequently called *machining centers*, where the motor-driven head moves vertically or in the z-direction while the table on which the work is mounted moves in the two horizontal or x- and y-directions, are common in machine and metal working shops.[53] These devices are extremely accurate, but can be too slow and too small for most

* The following items are extracted from Ref. 52.

plastics production trimming. Low-inertia x-y tables are used on plastics trimming machines, frequently called *CNC routers.* Furthermore, very low-inertia motor drives are used, with the drive head moving in three directions: the traditional z-direction and the u- and v-directions, where the u-direction allows tool rotation in the x-y direction and the v-direction allows tool rotation in the z-direction. The additional degrees of rotation allow the tool to move diagonally. Five-axis machines are less accurate than lathe-type machines but are faster and much more versatile. In certain instances, multiaxis robots have been used as trimming devices, but these devices are normally not robust enough to handle heavy trimming tools and high torques. Robotic accuracy is considered to be inferior to either three- or five-axis machines.

The keys to successful plastics trimming are cutter type or shape and cutting speed. Table 7.12 gives some additional factors.[54–56] Drill speeds for typical rotational molding polymers such as polyolefins and polycarbonates are 50 to 70 m/min. For soft polymers such as polyolefins, drill bits should have 10–20° helix angle, 70–90° point angle, and 9–15° clearance. For rigid

Table 7.12 Factors Affecting Cutting Characteristics of Plastics[58,59] (X = Major Effect; x = Minor Effect)

Factor	Chip Formation	Cut Surface Roughness	Tool Wear	Heat Generated	Gumming, Burning
Tool design					
Tool geometry*					
Rake angle	X				
Relief angle		X			
Point radius			X	x	
Tool material		X			
Machining conditions					
Depth of cut (Tooth depth of cut)	X		X	x	x
Cutting speed	X		X	x	x
Feeding speed	X		X		
Ambient work	x			X	X
Temperature/cooling system				X	X

* For single-edged cutting tools. Tool geometry effects are more complicated for multiple-edged cutting tools.

polymers such as nylons and polycarbonate, drill bits should have 17–27° helix angle, 80° point angle, and 9–15° clearance. Typical drill bit speeds are 10,000 to 25,000 rpm. For linear sawing or band sawing of polyolefins, blade speed and tooth pitch should decrease from 1300 m/min and 10–14 tpi* for parts with wall thicknesses of less than 10 mm to 500 m/min and 3 tpi for parts with wall thicknesses greater than 25 mm. For more brittle parts such as nylons and polycarbonate, linear blade speed and tooth pitch should decrease from 1000 m/min and 10-14 tpi for thin walled parts to 500 m/min and 3 tpi for thicker walled parts. Precision tooth form is recommended for cutting thin parts and buttressed tooth form is recommended for thicker parts.[57]

7.9 Surface Decoration

Because plastics can be brilliantly colored in the resin state, rotationally molded parts are usually used without further surface coloring or decoration. In certain instances, logos or instructions can be molded in as raised or depressed portions of the part surface, again without further surface coloring or decoration. There are many reasons to paint or otherwise decorate the rotationally molded part (Table 7.13):

Table 7.13 Painting or Decorating Rotationally Molded Parts

Color matching
Localized logo
Warnings or other instructions
Company product recognition
Metallized surface
Mirrored surface
Textured surface (not otherwise achieved with textured mold)
Chemical resistance
Ultraviolet resistance
Abrasion resistance
Unmoldable decorative effects

The nature of the polymer must be considered when the part demands further surface enhancement. For example, solvent-based paints will adhere

* *tpi* = teeth per inch.

quite well to PVC, PC, and most styrenics. On the other hand, chemical etching, flame treating, or other methods of surface activation prior to surface coating are required for polyolefins such as LLDPE, PP, and EVA, as well as many nylons.

7.9.1 *Painting*

If the rotationally molded part is to be painted, traditional spray painting techniques are used. In certain instances, a portion of the part may be silk-screened. This is a traditional process of expressing special ink through an appropriately masked screen onto the prepared plastic surface. Although the process is restricted to surface areas of 1 m^2 or so, the technique allows extremely fine details to be transferred to the plastic surface. Ink transfer techniques have been developed whereby a bladder-like mat is first pressed into an ink pad surface, which is then pressed onto the plastic surface. These techniques allow nonplanar surfaces to be imprinted with very fine details. Keep in mind that polyethylene is very difficult to paint unless the surface is properly treated. Flame treatment is quite effective and there are newer grades of polyethylenes that have been pretreated as powders to make the rotationally molded surface more receptive to paint. In most cases, however, molders avoid painting polyethylenes if possible.

7.9.2 *Hot Stamping*

Hot stamping provides yet another way of imparting surface treatment. A foil or film containing the appropriate printed, embossed, or textured surface on one side and a thermally compatible polymer film on the other is placed between the plastic surface and a hot plate. The hot plate presses the film or foil against the plastic surface, fusing the two together. If the surface to be transferred is perforated, the carrier foil is stripped from the fused surface as the hot plate is removed. Not only is hot stamping used to transfer some very elegant decals, but it is also used for such mundane tasks as imprinting the date and time of molding and even bar codes on otherwise undecorated parts.

7.9.3 *Adhesives*

Adhesive-backed decals are used extensively. The most popular adhesive today is the pressure-sensitive adhesive (PSA). Stripping off a carrier film commonly activates it. If the decal is to be permanent, the surface must be properly prepared so that the adhesive contacts as much of the polymer surface as possible and then chemically bonds to the polymer. In certain instances,

the decal is to be semipermanent. Protective films and assembly instructions are common applications of semipermanent decals. There are PSAs designed specifically for this application, but again the polymer surface must be properly prepared to minimize premature fall-off or undesirable permanent adhesion.

7.9.4 *In-Mold Decoration*

Recently, in-mold decoration has become popular. Here the decoration is applied to a rather substantial film of the polymer type being rotationally molded. This decoration is carefully placed and secured in the mold prior to powder filling. During heating, the polymer in the film melts and powder sticks to it. It is apparent when the cooled part is removed from the mold that the decoration is a true, permanent portion of the molded part. In-mold decoration seems to benefit by cavity pressure during the cooling stages. Color match is difficult with translucent decorations and decorations with substantial regions of polymer film show-through, since the polymer around the film and the polymer backing the film may oxidize at different rates, thus leaving an objectionable halo or shadow around the decoration. Care must also be taken during the early stages of rotation to prevent the dry powder from scuffing or lifting the decoration. In-mold decoration is more expensive than other postapplied surface treatments and improper placement or wrinkling of the decoration leads to an unacceptable part.

7.9.5 *Postmold Decoration*

Transfers, similar to those for in-mold use, have been developed that allow application to the finished molded part. Postmold decoration can reduce scrap rates since, unlike in-mold transfers, they do not get damaged or adhere improperly to the plastic during molding. The mold-on transfer becomes part of the surface of the molded plastic, making them durable and almost impossible to remove. Although these were developed for rotational molding, they are now being used with blow molded and thermoformed polyethylene parts.

7.9.6 *Internal Chemical Treatment*

As noted earlier, polyethylene is the dominant rotationally molded plastic. Most grades of polyethylene are quite chemically resistant. Polyethylene is crosslinked during rotational molding when additional chemical resistance is needed. Polypropylene also has excellent chemical resistance. With certain petroleum products and gasoline, additional chemical resistance may be needed.

One early technique flushed the inside of nylon 6 fuel tanks with hydrogen fluoride. Other treatments include washing of both nylon and LLDPE tanks with a solution of hydrofluoric and hydrochloric acid. It is thought that these acids chemically attack the polymer in the first few microns of the inner surface to form a fluorinated or chlorinated polymer layer that has greater chemical resistance or lower diffusional permeability. Polyolefins are particularly sensitive to sulfonation. As a result, fuming sulfuric acid is used to treat both polyethylene and polypropylene. It is thought that this technique causes chemical crosslinking, and as such, is a form of chemical vulcanization.[60]

7.10 Troubleshooting and Quality Assurance

Appendix A gives some general troubleshooting guidelines, but it is outside the scope of the book to detail the many ways of resolving process and product problems. Instead, it is recommended that the reader clearly understand the interaction and causal relationship between the polymer in its powder, melt, and solidifying state and the various parameters in the process, including mold materials, oven temperature, air circulation rate, cooling methods, and time. Furthermore, the reader should be aware of newer methods of process management, such as infrared mold surface temperature and internal mold cavity air temperature monitoring. And certainly, quality assurance (QA), not just with the finished product, but with incoming materials, is always critical to a well-run, trouble-free process. As detailed above, there are unique correlations between process parameter variations and final product property variations.

7.10.1 *Coordinate Measuring Machine*

One device that is growing in acceptance, both as a QA tool and as a tool for reverse engineering, is the coordinate measuring machine (CMM). The basic elements of a CMM are a touch-sensitive stylus mounted on a multiaxis arm, electronics that sense the position and orientation of the stylus, and a sophisticated software program that converts the electronics to graphical mode. CMMs range in size and cost from desktop digitizing tools costing a few thousand dollars to floor-mounted devices on granite tables, that cost tens of thousands of dollars. The obvious difference is in accuracy of the device. Inexpensive devices measure to ten-thousandths of an inch (0.010 inch) over a 50 inch span or 0.02% accuracy. Expensive devices measure to two-thousandths of an inch (0.0020 inch) over a 200 inch span or 0.001% accuracy.

The most obvious use for the CMM is in determining part-to-part dimensional variation. Simply, a part is fixtured on a table and the stylus is brought over and touched to specific locations. The data are logged, to be statistically compared with the required standard as well as the customer's specification.

Another use for the CMM is in reverse engineering. Here a finished part, a prototype design, or a pattern is fixtured on the table. The stylus is then traced in a continuous fashion over the surface. The computer software converts the data to a three-dimensional form, either as a wire form or a solid form. This digitized database can then be used to drive a CNC lathe to cut a mold, for example. Modifications, such as material shrinkage, can be included in the program.

A third use for the CMM is to program a CNC trimming device. Here, the stylus traces the to-be-trimmed lines and the coordinates are digitized and converted to the appropriate machine codes. The CMM is also used to locate drill holes. The CNC trimming device can drill properly sized holes, again with proper programming. It is important to realize that the trimming steps are coded directly from the molded part rather than from the original engineering drawings, thus ensuring more accurately dimensioned trimming.

Another use for the CMM is in developing a database for process- and material-dependent dimensional variations. When parts are originally designed, designers rely on generic shrinkage factors, such as those given in Table 7.6. Actual shrinkage may be strongly affected by process parameters such as oven temperature and time, material parameters such as molecular weight and crystallization rate, and part design, such as part wall thickness and part wall thickness variation. Therefore, the CMM is a useful tool in building databases that reflect these parametric changes. It is agreed that post-mortem part analysis is not profitable in the short run. But in the long run, these databases are invaluable in minimizing mold and process iteration.

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APPENDIX A. Troubleshooting Guide for Rotational Molding*

Problem	Probable Cause	Possible Solution	Location in Book
Long oven cycle	Excessively thick mold	Change to aluminum or beryllium-copper Reduce mold wall thickness	Section 5.1 Section 5.2
	Inefficient heat transfer	Increase air velocity Add baffles, venturis	Section 4.3.2 Section 4.3.3
	Poor polymer flow	Use higher melt index polymer	Section 2.9.1
	Poor powder flow	Change to a less sticky additive package Reclassify to remove tails Coarse particles	Section 3.10.6 Section 3.6 Section 3.2
Underfused parts	Insufficient heat transfer	Reduce mold wall thickness Change to aluminum molds Add baffles, venturis	Section 5.2 Section 5.1.2 Section 4.3.3
	Oven temperature too low	Increase oven temperature Increase heating time	Section 6.6–6.8 Section 6.6–6.8
	Oven time too short	Increase oven temperature Increase heating time	Section 6.6–6.8 Section 6.6–6.8
	Coarse powder	Check powder size, size distribution Replace micropellets with -35 mesh powder	Section 3.2 Section 3.8
Overcured parts	Oven temperature too high	Reduce oven temperature Decrease heating time	Section 6.6–6.8 Section 6.6–6.8
	Oven time too long	Reduce oven temperature	Section 6.6–6.8

Problem	Probable Cause	Possible Solution	Location in Book
		Decrease heating time	Section 6.6–6.8
	Wrong polymer	Change to less thermally sensitive polymer	Section 2.8
Poor impact strength	Wrong polymer	Select polymer with higher inherent impact, lower melt index, lower density	Section 2.2, 2.9
	High crystallinity due to long cooling time	Increase cooling rate	Section 6.20
	Insufficient powder fusion	Increase heating time	Section 6.6–6.8
		Increase oven temperature	Section 6.6–6.8
		Increase air velocity in oven	Section 4.3.2
		Change to aluminum molds, thinner mold walls	Section 5.2
	Bad part design	Increase corner radii	Section 7.6.5
		Increase distance between parallel walls	Section 7.6.8
	Wrong colorant	Change to pigment that doesn't interfere with impact or crystallization rate	Section 3.10
		Reduce level of masterbatched pigment	Section 3.10.4
		Use less pigment	Section 3.10
		Use precolored compounds	Section 3.10
	Overheated parts	[See comments for ***Overcured parts***]	
	Underfused parts	[See comments for ***Underfused parts***]	

Problem	Probable Cause	Possible Solution	Location in Book
Long-term part failure	Stress-cracking	Change to stress-crack resistant polymer	Section 2.2, 2.3
		Old or unstable polymer	Section 2.8, 2.9
		Redesign around inserts	Section 7.6.10
		Use low-stress-concentration inserts	Section 7.6.10
		Reconsider appropriateness of original design criteria	Section 7.3
	UV-degradation	Increase UV inhibitor level	Section 2.10.3
		Consider more expensive UV absorber	Section 2.10.3, 3.10.6
		Consider higher loading of carbon black	Section 3.10.4
Stress-cracking	Improper polymer	Change to stress-crack resistant polymer	Section 2.2, 2.3
	Improper part design	Redesign pert to minimize stress concentration	Section 7.6.7
		Use low-stress-concentration inserts	Section 7.6.10
	Long cooling time	Increase cooling rate to minimize shrinkage particularly around inserts, cores	Section 6.20
Nonuniform wall thickness	Improper mold rotation	Change speed and arm ratio	Section 4.2
		Use reverse rotation during heating	Section 4.2
	Improper mold design	Check mold wall thickness for nonuniformity	Section 5.2
		Move mold supports away from mold to prevent them from removing heat locally	Section 5.3.2
	Poor heat transfer	Move mold away from other molds, unstack molds to improve air circulation	Section 4.2, 4.3
		Add baffles, venturis for deep cavities	Section 4.3.3

Problem	Probable Cause	Possible Solution	Location in Book
Parting line bubbles	Poor mold parting line	Rework parting line	Section 5.3.1
		Redesign mold with tongue-and-groove parting line	Section 5.3.1
		Clean parting line of crud, recoat with mold release	Section 5.7
	Misaligned support frame	Rework support frame so mold halves seat properly	Section 5.3.2
	Inadequate venting	Resize vent	Section 5.5
		Reposition vent to middle of mold	Section 5.5
		Make certain glass wool is in vent tube	Section 5.5
		Use Teflon® vent tube	Section 5.5
		Use T-shaped vent tube	Section 5.5
Parts stick in mold	Inadequate draft on female parts of mold	Rework mold with larger draft angles	Section 7.6.5
		Coat locally with mold release	Section 5.7
	Heavily textured part	Coat with low coefficient of friction mold release	Section 5.7, 7.6.5
		Rework mold with larger draft angles	Section 7.6.5
	Lack of mold release	Strip off mold release and recoat	Section 5.7
		Recoat with higher temperature mold release	Section 5.7
		Recoat with lower coefficient of friction mold release	Section 5.7
		Recoat with mold release that is chemically compatible with polymer, additives, crosslinking agent, blowing agent	Section 5.7

Problem	Probable Cause	Possible Solution	Location in Book
	Mold surface damage	Look for undercuts, dings, dents, then rework mold	Section 7.6.5
	Flat area suction	Modify mold to allow air bleed into flat area	Section 5.3
		Roughen mold surface in flat area	Section 5.6
	Interference between part and mold	Remove incidental undercuts, rework mold to move parting line, add draft to mold	Section 7.6.5
		Remove part warm	Section 6.25
		Increase pry points on mold frame, use air-driven jack screws	Section 5.3.4
	Low-shrink polymer	Use higher density polymer	Section 2.2
Incomplete mold surface replication	Melt viscosity high	Use lower viscosity polymer	Section 2.2
		Increase oven temperature	Section 6.6–6.8
	Powder bridging	Check particle size, size distribution	Section 3.2
		Mix micropellets with powder	Section 3.8
	Cold spots on mold	Check local mold wall thickness [also see comments for ***Nonuniform Wall Thickness***]	Section 5.2
Bubbles in part	Trapped air	Reduce heating rate in last part of oven time	Section 6.20
		Reduce powder size	Section 3.2, 6.20, 6.21
		Increase powder size distribution	Section 3.2, 6.20, 6.21
		Increase vent size	Section 5.5
		Apply vacuum during last part of oven time	Section 6.15, 6.20
	Moisture	Adequately dry PMMA, PC, PVC drysols	Section 2.7

Problem	Probable Cause	Possible Solution	Location in Book
	Overcured part	Decrease oven time or temperature Use nitrogen purge throughout heating cycle [see comments for ***Overcured parts***]	Section 6.6–6.8 Section 6.15
	Outgassing	Change additive package in polymer Check pigment for thermal stability Replace temporary mold release with permanent mold release	Section 3.10.6 Section 3.10 Section 5.7
	Undercured part	Increase oven time or temperature [see comments for ***Underfused parts***]	Section 6.6–6.8
	Wrong polymer	Switch to polymer with higher melt index	Section 2.9.1
Bubbles along parting line	Poor parting line	Clean, rework parting line	Section 5.3.1
	Improper mold clamping	Rework mold clamping mechanism	Section 5.3.3
	Internal pressure during heating	Check, clear vent Increase vent size	Section 5.5 Section 5.5
	Internal pressure during cooling	Check, clear vent, replace glass wool Pressurize mold during cooling	Section 5.5 Section 6.15, 6.23
Blow holes around inserts	Moisture in polymer	Dry polymer, esp. PMMA, PC Apply vacuum during heating	Section 2.7 Section 6.15
	Adsorbed air on insert	Precoat insert with polymer	Section 5.3.5
	Bridging of powder at insert	Move insert away from bridging area Change insert to more open design Replace metal insert with plastic one	Section 7.6.9 Section 7.6.10 Section 7.6.10

Problem	Probable Cause	Possible Solution	Location in Book
Flash at parting line	Poor parting line	Clean, rework parting line	Section 5.3.1
		Increase clamping force	Section 5.3.3
		Rework mold clamping mechanism	Section 5.3.3
	Internal pressure buildup	Check, clear vent, replace glass wool	Section 5.5
		Increase vent size	Section 5.5
	Low polymer viscosity	Decrease polymer melt index	Section 2.9.1
		Lower oven temperature	Section 6.6–6.8
Warped parts	Inadequate venting	Increase vent size	Section 5.5
		Replace glass wool	Section 5.5
	Nonuniform cooling	Maintain rotation during cooling	Section 6.18
		Increase air cooling time	Section 6.21
		Check vent size, glass wool quality	Section 5.5
		Rework mold to replace flat areas with ribbed, corrugated, domed areas	Section 5.3
		Increase water coolant temperature	Section 6.23
		Minimize, remove mold release	Section 5.7
		Use air pressure during water cooling time	Section 6.15, 6.23
		Reduce rate of external cooling	Section 6.21, 6.22
		Introduce internal cooling	Section 6.24
	Overcured part	Decrease oven temperature	Section 6.6–6.8
		Decrease oven time	Section 6.6–6.8
		Use nitrogen purge throughout heating cycle	Section 6.15

Problem	Probable Cause	Possible Solution	Location in Book
	Underfused part	Increase oven temperature, time	Section 6.6–6.8
		Increase heat transfer by using aluminum molds	Section 5.2
		Use thinner molds	Section 5.1
		[see comments for ***Underfused parts***]	
	Wall thickness variation	Check rotation ratio	Section 4.2
		Remove, minimize hot spots on mold	Section 5.2
		Increase cooling rate	Section 6.21, 6.22
	Local part separation from wall	Use internal pressure during cooling	Section 6.15
	Poor parting line	Improve mating surfaces on mold	Section 5.3
		Clean thoroughly mating surfaces on mold	Section 5.3
	Blocked vent	Inspect vent before each cycle	Section 5.5

* Adapted from J. Bucher, "A Beginner's Guide to Rotomolding," Plastics World, **48**:7 (July 1997), pp. 14-16.

APPENDIX B. Conversion Table

Metric		to	U.S.		to	Metric
Length						
m	×	3.28	ft	×	0.3048	m
μm	×	10^{-6}	m	×	10^{6}	μm
km	×	1.609	mile	×	0.622	km
mm	×	39.37	mils	×	0.0254	mm
Area						
m^2	×	10.76	ft^2	×	0.0929	m^2
cm^2	×	0.155	in^2	×	6.452	cm^2
mm^2	×	1.55×10^{-3}	in^2	×	645.2	mm^2
Volume						
m^3	×	35.31	ft^3	×	0.02832	m^3
m^3	×	$6.102 \times l0^4$	in^3	×	1.639×10^{-5}	in^3
mm^3	×	$6.102 \times l0^{-5}$	in^3	×	$1.639 \times l0^4$	mm^3
liter	×	1000	cm^3	×	0.001	liter
cm^3	×	29.57	fluid oz	×	0.0338	cm^3
m^3	×	264.2	U.S. gal	×	$3.785 \times l0^{-3}$	m^3
Mass						
g	×	0.0022	lb_m	×	453.6	g
kg	×	2.204	lb_m	×	0.4536	kg
kg	×	0.001	metric tonne	×	1000	kg
kg	×	0.0011	U.S. ton	×	907.2	kg
Density						
g/cm^3	×	62.42	lb_m/ft^3	×	0.016	g/cm^3
kg/m^3	×	0.06242	lb_m/ft^3	×	16.02	kg/m^3
g/cm^3	×	0.578	oz/in^3	×	1.73	g/cm^3
kg/m^3	×	$5.78 \times l0^{-4}$	oz/in^3	×	$1.73 \times l0^3$	kg/m^3
Force						
N	×	0.2248	lb_f	×	4.448	N
kg_f	×	0.2292	lb_f	×	4.363	kg_f
kN	×	0.2248	kip, 1000 lb_f	×	4.448	kN
dyne	×	2.248×10^{-6}	lb_f	×	4.448×10^5	dyne
dyne	×	10^{-5}	N	×	10^5	dyne

Metric		to	U.S.		to	Metric
Pressure						
Pa	×	1.45×10^{-4}	lb_f/in^2	×	6895	Pa
MPa	×	9.869	atm	×	0.1013	MPa
Pa	×	10	dyn/cm^2	×	0.1	Pa
Pa	×	7.5×10^{-3}	1 mm Hg	×	133.3	Pa
Pa	×	4.012×10^{-3}	1 in H_2O	×	248.9	Pa
MPa	×	10	bar	×	0.1	MPa
N/mm^2	×	145	lb_f/in^2	×	6.895×10^{-3}	N/mm^2
Energy						
J	×	9.478×10^{-4}	Btu	×	1055	J
ft-lb_f	×	1.286×10^{-3}	Btu	×	778	ft-lb_f
J	×	0.2388	cal	×	4.187	J
J	×	1×10^7	erg	×	1×10^{-7}	J
MJ	×	2.778×10^{-7}	kW hr	×	3.60×10^6	MJ
J	×	0.7375	ft-lb_f	×	1.356	J
Energy, Power, Heat, Fluid Flow Rate						
W	×	3.413	Btu/hr	×	0.293	W
W	×	1×10^7	erg/s	×	1×10^{-7}	W
W	×	0.7375	ft-lb_f/s	×	1.356	W
kW	×	1.34	hp	×	0.746	kW
liter/min	×	0.2642	gal/min	×	3.785	liter/min
liter/min	×	2.393	ft^3/hr	×	0.4719	liter/min
Heat Flux						
W/m^2	×	0.317	Btu/hr ft^2	×	3.155	W/m^2
cal/s cm^2	×	3.687	Btu/hr ft^2	×	0.2712	cal/s cm^2
W/m^2	×	6.452×10^{-4}	W/in^2	×	1550	W/m^2
Specific Heat						
J/kg K	×	2.388×10^{-4}	Btu/lb °F	×	4187	J/kg K
cal/g °C	×	1	Btu/lb °F	×	1	cal/g °C
Thermal Conductivity						
W/m K	×	0.5777	Btu/hr ft °F	×	1.731	W/m K
W/m K	×	1.926×10^{-3}	Btu in/s ft^2 °F	×	519.2	W/m K
W/m K	×	7.028	Btu in/hr ft^2 °F	×	0.1442	W/m K
W/m K	×	2.39×10^{-3}	cal/cm s °C	×	418.4	W/m K

Metric		to	U.S.		to	Metric
Velocity						
km/hr	×	0.6205	miles/hr	×	1.609	km/hr
m/s	×	3.6	km/hr	×	0.2778	m/s
m/s	×	39.37	in/s	×	0.0254	m/s
m/s	×	3.281	ft/s	×	0.3048	m/s
m/s	×	1.181×10^{4}	ft/hr	×	8.467×10^{-5}	m/s
Mass Flow Rate						
kg/s	×	7.937×10^{3}	lb/hr	×	1.26×10^{-4}	kg/s
kg/s	×	2.205	lb/s	×	0.4536	kg/s
Viscosity						
Pa s	×	10	Poise	×	0.1	Pa s
Pa s	×	1000	centipoise	×	0.001	Pa s
m^2/s	×	10.76	ft^2/s	×	0.0929	m^2/s
Pa s	×	1.488	lb/s ft	×	0.672	Pa s
centipoise	×	1488	lb/s ft	×	0.000672	centipoise
m^2/s	×	1×10^{6}	centistoke	×	1×10^{-6}	m^2/s
Pa s	×	1.45×10^{-4}	lb_f s/in^2	×	6.895×10^{3}	Pa s
Pa s	×	2.088×10^{-2}	lb_f s/ft^2	×	47.88	Pa s
Stress						
MPa	×	145	lb_f/in^2	×	6.895×10^{-3}	MPa
MPa	×	0.102	kg_f/mm^2	×	9.807	MPa
MPa	×	0.0725	ton_f/in^2	×	13.79	MPa
MPa	×	1	MN/m^2	×	1	MPa
MPa	×	1	N/mm^2	×	1	MPa
Bending Moment						
Nm	×	8.85	lb_f in	×	0.113	Nm
Nm	×	0.7375	lb_f ft	×	1.356	Nm
Nm/m	×	0.2248	lb_f in/in	×	4.448	Nm/m
Nm/m	×	1.873×10^{-2}	lb_f ft/in	×	53.38	Nm/m
Fracture Toughness and Impact Strength						
MPa $m^{1/2}$	×	0.9099	ksi $in^{1/2}$	×	1.099	MPa $m^{1/2}$
J/m	×	0.2248	ft lb_f/ft	×	4.448	J/m
J/m	×	0.01874	ft lb_f/in	×	53.37	J/m
J/m^2	×	4.757×10^{-4}	ft lb_f/in^2	×	2102	J/m^2

Author Index

A

Andrzejewski, S., 11, *16*
Arendt, W.D., 6, *15*, 96, *109*
Arpaci, V.S., 247, *302*
Ashby, M.F., 325, 327, *363*
Astarita, T., 210, 211, *300*
Astarita, G., 210, 211, *300*
Attaran, M.T., 248, *302*

B

Balmer, R.T., 279, 282, *304, 305*
Bawiskar, S., 138, *147*
Beall, G.L., vi, 2, *14*, 112, *147*, 160, *200*, 206, 276, 285, *299, 304, 305,* 307, 310, 313, 318, 319, 335, 340, 342, 344, 349, 351, *362, 364*
Becker, H., 4*, 14*
Bellehumeur, C.T., 11, *17*, 20, 69, 93, *108*, 225, 228, 234, 243, 244**,** *301, 302,* 354, *365*
Benning, C.J., 28, 59, 60, *65, 68*
Bent, A.A., 210, *299*
Berins, M.L., 335, 356, *364, 365*
Bisaria, M.K., 6, 11, *15, 17*
Boenig, H.V., 42, *66*
Boersch, E., 1, *14*, 96, 104, *109*
Bonis, L.J., 225, *300*
Bothun, G., 104, *110*
Braeunig, D., 6, *15*
Brown, R.L., 205, 211, 212, *299*
Bruins, P.F., vi, 4, *14*, 40, *66*, 112, *147*
Brydson, J.A., 20, *65*, 211, *300*
Bucher, J., 4, *14*, 367, *374*
Burnett, D.S., 333, 335, *363, 364*
Burns, M., 332, *363*

C

Calafut, T., 28, *65*
Campbell, C.S., 210, *300*
Carrino, L., 104, *110*
Carter, B., 4, *14,* 113, *147*
Cellier, G., 236, 237, 242, *301*
Cerro, R.L., 279, 281, *304, 305*
Chabot, J.F., 4, *14*
Chan, L.S., 6, *16*, 69, *108*
Chen, C.-H., 146, *148*, 201, 214, 247, 248, *299*
Cheney, G., 11, *16*
Chiou, Y.H., 228, 229, 237, *301*
Clark, D.T., 360, *365*
Collins, E.A., 38, *65*
Copeland, S., 6, *15*, 64, *68*
Covington, H., 335, *364*
Cowan, S.C., 210, *299*
Cramez, M.C., 12, *17, 18***,** 99, *109*, 268, *303*
Crawford, R.J., vi, 1, 2, 6, 11, 12, *14–18*, 69, 85, 90, 94, 99, 100, *108, 109*, 112, 120, 138, 140, 142, 146, *147, 148*, 186, *200*, 201, 207, 214, 238, 240, 248, 268, *299, 302*, *303*, 318, 319, 323, 348, 349, 350, 352, 353, 354, *362, 364, 365*
Crouch, J., 146, *148*
Cumberland, D., 85, *109*

D

de Bruin, W., 69, 90, 92, *108*
Dieber, J.A., 279, 281, *304, 305*
Dodge, P., 11, *16*
Domininghaus, H., 20, *65*, 338, 339, *364*
Dority, S., 101, *109, 110*
Dusinberre, G.M., 266, *303*
D'Uva, S., 287, 306

E

Eilers, K., 330, *363*
Elias, H.-G., 267, 268, *303*
Epstein, P.S., 240, *302*
Ezrin, M., 56, *67*, 307, *362*

F

Fahnler, F., 39, *66*
Fawcett, J., 332, *363*
Fayed, M.E., 219, *300*
Feast, W.J., 360, *365*
Fenner, R.T., 333, *363*
Findley, W.N., 323, *362*
Flannery, B.P., 333, *363*
Fogler, H.S., 239, *302*
Foy, D., 101, *110*
Frenkel, Ya.I.., 225, *300*
Frisch, K.C., 59, *67*, 291, *306*

G

Gachter, R., 63, *68*
Gebhart, B., 333, *363*
Gianchandani, J., 6, *16*, 279, 282, 283, *304, 305*
Gibson, L.J., 325, 327, *363*
Goddard, J.D., 239, *302*
Gogos, G., 142, *148*, 240, 250, 251, 273, 274, *303*
Goodman, M.A., 210, *299*
Goodman, T.R., 249, *302*
Gotoh, K., 81, *108*
Graham, B., 6, *15*, 58, 64, *68*

H

Han, C.D., 239, *302*
Hang, C.C., 6, *16*, 69, *108*
Harkin-Jones, E.M.A., 6, *16,* 38, 39, 40, 41, 42, *65, 66*, 69, *108,* 279, 282, 283, 284, *303, 304, 305*
Hartnett, J.P., 250, 261, *303*
Hausner, H.H., 225, *300*
Hentrich, R., 154, *200*
Hickey, H.F., 40, *66*
Higashitani, K., 81, *108*
Howard, H.R., 11, *16*, 101, *109, 110*
Huebner, K.H., 333, *363*

I

Iwakura, K., 146, *148*, 201, 214, 247, 248, *299*

J

Joesten, L., 6, *16,* 64, *68*
Johnson, L., 105, *110*
Johnson, R.E., 279, 281, *304, 305*
Jolly, R.E., 44, 66

K

Kampf, G., 44, 56, *66*
Keurleker, R., 39, *66*
Khemani, K.C., 291, *305*
Kinghorn, K.B., 6, *15*
Klempner, D., 59, *67*, 291, *306*
Kobayashi, A., 356, *365*
Kontopoulou, M., 6, 11, *15, 17*, 64, *68*, 234, 238, 240, 241, 243, 244, *301, 302*, 354, *365*
Kreith, F., 205, 215, 216, *299, 300*, 335, *364*
Kuczynski, G.C., 225, *300*
Kumar, S., 328, *363*
Kurihara, K., 210, 211, *299*

L

Lai, J.S., 323, *362*
Landrock, A.H., 291, *306*
Lang, J., 6, *15*, 96, *109*
Lefas, J.A., 287, *306*
Levitskiy, S.P., 231, 238, *301, 302*
Lin, S.T., 228, 229, 238, *301*
Liniger, E.G., 211, *300*
Linoya, K., 81, *108*
Lipsteuer, S.J., 93, *109*, 287, *306*
Liu, F., 287, *306*
Liu, G., 287, *306*
Liu, S.-J., 228, 229, 238, *301*
Liu, X., 250, 273, 274, *303*
Lontz, J.F., 225, *300*
Lowe, J., 6, *15*

Lui, S.-J., 11, *17*
Lun, C.K.K., 210, *299*

M

Macauley, N., 270, *303*
MacKinnon, C., 191, *200*
Maier, C., 28, *65*
Malkin, B.A., 279, 280, *305*
Malloy, R.A., 315, 322, 323, 345, 346, *362–364*
Malwitz, N., 291, *305*
Mansure, B., 6, *15*
Marchal, J.-M., 287, *306*
Marion, R.L., 278, *304*
Martin, D., 6, *16*, 69, *108*
Mazur, S., 225, 226, 227, 228, 232, 233, *301*
McCarthy, T.J., 360, *365*
McClellan, E., 6, *15*
McDaid, J., 69, 70, 71, 73, 76, 86, 89, 90, 91, 94, *108*
McDonagh, J.M., 6, *15*
Mello, J., 335, *364*
Mincey, E., 105, *110*
Mish, K.D., 335, *364*
Mooney, P.J., 1, *14*
Morawetz, H., 22, 30, *65*
Moroni, G., 104, *110*
Muller, B., 6, *15*, 101, 102, *110*
Muller, H., 63, *68*
Murphy, W.R., 270, *303*
Muzzio, F.J., 243, *306*

N

Nagy, T., 100, *109*
Nakajima, N., 38, *65*
Narkis, M., 25, *65,* 218, 225, 226, 227, 228, 232, 233, 235, 236, *301*, 347, 348, *364*
Neuville, B., 225, *300*
Newman, S.J., 236, *301*
Nickerson, J.A., 2, *14*
Nugent, P.J., 11, 12, *16–18*, 140, *147*, 186, *200*, 201, 214, 273, 274, *299, 303*, 350, 352, 353, 354, *365*

O

Ocone, R., 210, 211, *300*
Ogorkiewicz, R.M., 4, *14*, 44, 52, *66, 67*, 268, 270, 271, 272, *303*
Ohta, Y., 146, *148*, 201, 214, 247, 248, *299*
Okoroafor, M.O., 291, *306*
Oliveira, M.J., 12, *17, 18*, 99, *109*, 268, *303*
Olson, L.G., 250, 273, 274, *303*
Onaran, K., 323, *362*
Onoda, C.Y., 211, *300*
Orr, J., 6, *16*, 69, *108*
Otten, L., 219, *300*

P

Paiva, M.C., 12, *18*
Park, C.P., 59, *67*, 291, *306*
Park, C.L., 287, *306*
Pasham, V.R., 250, *303*
Passman, S.L., 210, *300*
Peterson, A.C., 315, *362*
Petrucelli, F., 6, *15*
Pietsch, W., 81, *109*
Plesset, M.S., 240, *302*
Polini, W., 104, *110*
Pop-Iliev, R., 287, *306*
Press, W.H., 333, *363*
Progelhof, R.C., 20, 22, 23, 44, 45, 50, 53, 62, 63, *65–68,* 217, 229, 230, 231, 236, 237, 242, 267, 279, *300, 301, 303, 304*, 315, 323, 328, 330, *362, 363*

Q

R

Rabinovitz, E., 6, *16*
Ramesh, N.S., 291, *305*
Rao, M.A., 81, *108*, 201, 205, 214, *299*
Rauenzahn, R.M., 210, 211, *300*
Rauwendaal, C., 207, *299*
Rees, R.L., 6, *15*, 76, *108*
Rhodes, M., 77, *108*
Richards, J.C., 205, 211, 212, *299*
Rigbi, Z., 6, *16*
Rijksman, B., 287, *306*
Roark, R.J., 318*, 362*
Rohsenow, W.H., 250, 261, *303*
Rosenzweig, N., 25, *65*, 218, 225, 226, 227, 228, 232, 233, 235, 236, *301*, 347, 348, *364*
Ruetsch, R.R., 217, *300*
Rumpf, H., 205, *299*

S

Saffert, R., 6, *15*
Sarvetnick, H.A., 37, 38, *65*, 278, *304*
Schmitz, W.E., 4, *14*
Schneider, K., 39, *66*
Schneider, P.J., 249, 250, 261, *303*
Scott, J.A., 12, *17*, 142, *147, 148*
Shah, V., 44, 51, 54, 57, 61, 62, *66–68*
Shinbrot, T., 243, *306*
Shinohara, K., 219, *300*
Shrastri, R.K., 48, 49*, 67*
Shulman, Z.P., 231, 238, *301, 302*
Shutov, F.A., 289, 291, 293, *305, 306*
Silva, C., 100, *109*
Sin, K.K., 6, *16*, 69, *108*
Smit, T., 69, 90, 92, *108*
Sneller, J., 287*, 306*
Sohn, M.-S., 83, *109*, 205, 211, *299*
Sowa, M.W., 6, *16*
Spence, A.G., 12, *17*, 89, 100, *109,* 138, 142, 146, *147, 148*, 207, 238, 240, *299, 302*
Spyrakos, C.C., 266, *303,* 310, 333, 334, *362, 363*
Stanhope, B.E., 6, *15,* 96, *109*
Stoeckhert, K., 154, *200*
Strebel, J., 89, 90, 91, *109*
Strong, A.B., 6, *15*
Stufft, T.J., 89, 90, 91, *109*
Susnjara, K., 355, *365*
Swain, R., 102, *110*
Syler, R., 242, *302*

T

Takacs, E., 64, *68*, 69, 93, *108*, *109*, 243, 244, 287, *302, 306*, 354, *365*
Tanaki, A., 36, *68*
Taylor, T.J., 348, *364*
Teoh, S.H., 6, *16*, 69, *108*
Teukolsky, S.A., 333, *363*
Throne, J.L., 6, 10, *16*, 20, 22, 23, 25, 44, 45, 50, 53, 62, 63, *65–68*, 81, 83, *108, 109*, 201, 205, 207, 210, 214, 215, 217, 218, 224, 229, 230, 231, 235, 236, 237, 238, 239, 242, 245, 246, 247, 248, 251, 267, 275, 279, 281, 282, 283, 288, 291, 293, *299–305*, 308, 315, 323, 327, 328, 323, 330, 331, 340, 341, 347, 348, 356, *362–365*
Tordella, J.P., 44, *66*
Tredwell, S., 64*, 68*
Turner, S., 47, *67*
Turng, L.-S., 287, *306*

U

V

Vetterling, W.T., 333, *363*
Vincent, P.I., 52, *67*
Vlachopoulos, J., 6, 11, *15, 17*, 64, *68*, 69, 93, *108, 109*, 225, 228, 234, 238, 240, 241, 243, 244, 287, *301, 302, 306*, 354, *365*
Voldner, E., 6, *15*

W

Walls, K.O., 12, *18*
Wang, H.P., 287, *306*
Ward, D.W., 38, *65*
Ward, W.J., 360, *365*
Weber, G., 4, *14*
Werner, A.C., 37, 38, *65*
White, J.L., 100, *109*, 138, *147, 148*, 201, 214, 247, 248, *299*
Wisley, B.G., 6, *16*
Wright, M.J., 138, 120, *147*
Wright, E.J., 248, *302*
Wytkin, A., 120, *147*

X

Xin, W., 11, *16*
Xu, L., 240, *302*

Y

Yoo, H.J., 239, *302*
Young, W.C., 318, *362*

Z

Zhang, D.Z., 210, 211, *300*
Zimmerman, A.B., 4, *14*

Index

Figure entries are suffixed “F” and those with “T” refer to tables.

Index terms	Links
A	
ABS	9
See also Acrylonitrile-butadiene-styrene	
Rotational molding grade, discussed	36
Limitations in rotational molding	36
Acrylic	9
See also PMMA, Polymethyl methacrylate	
Acrylonitrile-butadiene-styrene	
As thermoplastic	19
Discussed	35
Air temperature, inner cavity, measurement	140
Air solubility in polymer	239
Aluminum casting	
See also Mold, aluminum, cast	
Procedure	152
Amorphous, defined	20
ARM, *see* Association of Rotational Molders	
Arms	
Design weight, described	122
Hollow for inert gas injection	146
Hollow for pressuring molds	146
Offset	122
Straight	122

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Arms *(Continued)*				
Support of molds	122	122F		
Swing diameter				
Described	123	123F	124F	125F
Examples of	123			
Association of Rotational Molders	12			
ASTM D-1238	24			
See also Melt index				
ASTM D-1693	22			
See also ESCR; Environmental stress crack test				
ASTM D-348	26	32		
See also Heat distortion temperature				
ASTM D-2765	27			
See also Polyethylene, crosslinked				
ASTM D-1238	44			
ASTM E-11	46			
See also Sieve, screen sizes, discussed				
ASTM D-1921	46			
See also Sieve technology				
ASTM D-1505	51			
See also Density gradient column				
ASTM D-256	53			
See also Impact test, pendulum; Impact test, Charpy; Impact test, Izod				
ASTM D-3029	53			
See also Impact test, falling weight				
ASTM D-790	54			
See also Mechanical test, flexural modulus				
ASTM D-638	64			
See also Mechanical test, tensile modulus				

This page has been reformatted by Knovel to provide easier navigation.

Index terms		Links
ASTM D-2990	55	
See also Mechanical test, creep		
ASTM D-671	55	
See also Mechanical test, flexural fatigue		
ASTM D-1693	58	
See also Environmental stress crack test, notched strip		
ASTM D-1435	61	
See also Weathering, accelerated tests		
ASTM D-3801	63	
See also Fire retardancy, standard match test		
ASTM D-2863	63	
See also Fire retardancy, oxygen index		
ASTM E-11	75T	
See also Sieve		
ASTM D-1921	76	
See also Particle size distribution		
ASTM D-1895	84	84F
See also Powder flow, test method		
ATM D-1895	46	
See also Sieve technology, bulk density; Sieve technology, pourability		
Attrition	69	
See also Pulverization, described		

B

Baffles		
See also Molds		
In mold design	136	136F
Bridging, considerations for	311	
Brittle fracture, impact test	51	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
Brittle temperature for several polymers	52		
Bubbles	15		
Bulk density			
Grinding factors affecting	89		
Powder			
Fluidized	88T		
Measurement	84F	88	
Poured	88	88T	
Tamped	88	88T	
Vibrated	88	88T	

C

CAB, *see* Cellulose acetate butyrate			
CAP, *see* Cellulose acetate propionate			
Carousel machine			
Fixed arm	117	118F	
Independent arm	118	119F	
Cellulose acetate butyrate, discussed 34			
Cellulose acetate propionate, discussed	34		
Cellulosic	9	21	
Discussed	34		
General properties, discussion	35		
Centrifugal casting	7	15	
Charge weight, calculation of	174		
For cylinder	175	175F	
For rectangle	176	176F	177F
For various shapes	177	179T	
Chemical resistance, post-applied	359		

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links	
Chemical test		
Crazing	57	
Haze formation	56	
Plasticization	56	
Solvation	56	
Solvent migration	56	
Stress-cracking	57	
Chocolate	7	
Clamshell machine		
Discussed	115	115F
Oven design	116	
Coalescence	26	
As sintering	26	
Effect of particle size distribution on	87	
Color		
CIE standard	56	
Compounding	96	101
Dry blending	96	
Concentration level effect	99F	
High speed mixing	97	
Low-intensity	97	
Low-intensity, equipment	97	
Tumbling	96	97
Turbo-blending	97	
Effect of blending technique on dispersion of	100F	
Effect of blending technique on mechanical properties	101	
Factors that affect	55	
Methods of, discussed	96	
Rotational molding factors that affect	56	
XYZ diagram	56	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
Cooling			
Air	137	274	
Cycle time for			
Discussion	259		
Mathematical model	260	262	
Wall thickness effect on	277		
Discussed	137		
Effect on shrinkage/warpage	137		
Effect of water quench on	275		
Experimental and theoretical comparison of	273	274F	
Part release from mold during	203F	204	
Pressurized mold	276		
Recrystallization during	203F	204	
Recrystallization effects during	266		
Recrystallization effects during, modeling			
Temperature measurements during	202F	203F	
Thermal inversion			
Described	262		
Technical description	262	263F	264F
Distributed parameter model	264		
Lumped parameter model	266		
Water spray/mist	137		
Cooling methods, discussed	137		
Cooling rate	16		
Coordinate measuring machine, discussion	360		
Cracking, localized, impact test	51		
Crazing	57		
Creep modulus, *see* Mechanical test, creep modulus; Mechanical test, creep			
Crystallinity, defined	20		

This page has been reformatted by Knovel to provide easier navigation.

Index terms **Links**

D

Decoration
- Adhesives 358
- Hot stamping 358
- In-mold 359
- Methods of, discussion 357 357T
- Painting 358
- Post-mold 359

Design
- Of molds, *see* Molds, design of
- Of parts, *see* Parts, design of; Parts design
- Part removal 276

Design, mechanical
- CAD/CAM in 332
- Cantilever beam flexural 316
- Column bending 317
- Computer-aided stress analysis for 332
- Computer-aided stress analysis for; *see Finite-element analysis*
- Computer aids for, discussed 330 331F
- Computer aids in prototyping 332
- Greep in 322
- Criteria for parts 314
- Finite difference analysis for 333
- Finite-element analysis for 333
- Foams, discussion 324
  - Skin-core foams
    - Stiffness of 329
    - I-beam model for 329 330F
    - Polynomial beam model, discussed 330 331F

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Design, mechanical *(Continued)*				
Uniform density foams	324			
Stiffness of	325			
Modulus for	325			
Foaming efficiency of	325	326T		
Tensile strength for	327			
Impact characteristics of	327	328T		
Ductile-brittle characteristics of	327	328F		
Hollow beam with kiss-off	318			
Long-term loading	314			
Moderate-term loading	314			
Plate bending, edge-on	317			
Ribbed plate	319			
Short-term loading	314			
Temperature-dependency in	323	324T		
Tensile creep in	323	323F		
Three-point flexural	315			
Demolding, schematic	5	2F		
Density gradient column	51			
Density, polyethylene property changes with	25T			
Differential Scanning Calorimetry	268	270	271F	272F
DIN 6174	56			
See also Color, CIE standard				
DIN 5033	56			
See also Color, XYZ diagram				
Distortion	16			
Dry blender				
Double-cone	97	98F		
Double-ribbon	97			
Vee mixer	97	98F		

This page has been reformatted by Knovel to provide easier navigation.

Index terms		Links
Dry blending		
See also Color		
Additives in melt-blending	98	
Additives in tumble-blending	97	
Additives suitable for	97	
Effect on mechanical properties	99	
Effect on polymer crystalline nucleation	99	
Effect on polymer morphology	99	
Henschel-type mixer	99	
Rotational molding powders	97	
Turbo mixing	99	
Drying conditions for polymers	34T	
Ductile failure, impact test	51	
Ductile yield, impact test	51	
Ductile-brittle transition, impact test	52	52F
E		
Electroformed nickel		
Procedure	155	
See also Molds, electroformed nickel		
Environmental stress crack resistance, LDPE	50	50F
Environmental stress crack test		
Bent strip	57	57F
Constant stress test	58	
Defined	57	
Notched strip	58	
Polyethylene	58	
Epoxy	9	
As liquid polymer	37	
ESCR, *see* Environmental stress crack test		

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links
Ethylene vinyl acetate	
Chemical structure 27	
Density 28	
Environmental stress crack resistance 28	
Extent of vinyl acetate 28	
Foamability 28	
Melt temperature range 28	
Shore hardness 28	
EVA, *see* Ethylene vinyl acetate	
F	
FDE, *see* Finite difference analysis	
FEA, *see* Finite-element analysis	
FEP, *see* Fluoroethylene polymer	
Finite difference analysis 333	
Finite-element analysis 333	
Arithmetic for 334	
Formalization of 334T	
Limitations of 335	
Fire retardancy	
Defined 62	
Oxygen index 63	63T
Standard match test 63	
Flexural modulus, *see* Mechanical test, flexural modulus	
Fluorocarbon 9	
Fluoroethylene polymer, as thermoplastic 19	
Foam rotational molding	
Blowing agent efficiency in 290	
Bubble nucleation in 291	
Chemical foaming agents for 287	288T 289T

This page has been reformatted by Knovel to provide easier navigation.

Index terms		Links
Foam rotational molding *(Continued)*		
Endothermic	288	
Exothermic	288	
Containerized inner layer in	298	
Diffusional bubble growth in	291	
Discussed	287	
Inertial bubble growth in	291	
Limitations of	292	
One-step process in	295	
Oven conditions for	293	293T
Physical foaming agents for	287	
Single layer structures in	295	
Skin/core structure in	287	
Terminal bubble growth in	292	
Two-step process in	296	
Fracture, brittle, impact test	51	

G

Glass transition temperature, defined	20	
Grinding	69	
See also Pulverization, described		
Ball-mill	69	
Costs associated with		
Discussion	91	
Factors	92	
Economies of scale	92	
Frictional heat	71	
Gap size effect on powder quality	89	
Hammer-mill	69	
Horizontal mill	72	73F

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
Grinding *(Continued)*			
In-house v. outsourcing	91		
Mill tooth number effect on powder quality	90		
Parallel plate	69		
Particle sieving	71		
Powder characteristics	73		
Particle size distribution	74		
Flow	74		
Bulk density	74		
LLDPE	74		
As related to rotational molding parameters	74	75	
Particle shape	75		
Process control	72		
Process equipment	69F	72F	
Skill factors involved in	92		
Temperature effect on powder quality	90	90F	91F
Vertical mill	70	70F	
H			
Haze formation	57		
HDPE			
Crystallinity of	20T		
See also Polyethylene, high-density			
Heat capacity, of powder	218		
Heat transfer			
Coefficient of			
For air	274		
For water	275		
Combustion	129	130T	
Conduction	213		

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Heat transfer *(Continued)*				
Defined	127			
Convection	213			
Defined	127			
Coefficient	127	127T		
Effect of polymer morphology on	243	244F		
Modes, defined	127			
Radiation	213			
Defined	127			
Thermal lag in mold	214	222	245	
To coalescing powder bed	223			
To powder	215			
To powder bed	217			
To powder particle	215			
To mold	213			
To mold assembly	139			
To mold assembly, measurements of	139	139F		
Transient heat conduction in	216F			
Transient heat conduction model	247			
Types in rotational molding	213			
Heating				
See also Oven; Heat transfer				
Cycle time of	251			
Actual	258T			
Oven temperature effect on	255T	256	256T	258
Thickness effect on	254	255T	256	256T
Direct-gas impingement	113			
Discussion of	201			
Effect of pressure on powder behavior during	244			
Effect of vacuum on powder behavior during	244			

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Heating *(Continued)*				
Kink temperature during	202	203F	220	253
Mathematical modeling of	245	246F		
Mold cavity air temperature during	221			
Mold energy uptake to polymer uptake ratio	252			
Polymer morphology effect on rate of	223	224F		
Temperature measurements during	201	202F	203F	
Time to inner cavity temperature, thickness effect on	255			
Time to kink temperature, thickness effect on	255			
Overall cycle time, thickness effect on	256	257F		
Henry's law	239			
And foam rotational molding	293			
I				
Igepal	22	23	24	27
	28	49	58	
Impact, process effects on	350	350F	353F	354F
Impact test				
Charpy	53			
Constant velocity puncture	53			
Described	51			
Failure type	51			
Factors affecting	53			
Falling weight	53			
Bruceton method	53			
ARM standard, *see* Impact test, falling weight, Bruceton method				
ARM standard, low-temperature, *see* Impact test, falling weight, Bruceton method				
Probit method	53			

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Impact test *(Continued)*				
Staircase method, *see* Impact test, falling weight, Bruceton method				
"Up-and-down" method, *see* Impact test, falling weight, Bruceton method				
Izod	53			
Low-temperature, ARM terms	52			
Pendulum	53			
Test types	53			
Tensile	53			
L				
Latex rubber	7			
LDPE				
See also Polyethylene, low-density				
Crystallinity of	20T			
Environmental stress crack resistance, melt index effect	50	50F		
Liquid polymers	69			
Discussed	36			
Liquid rotational molding				
Bubble entrainment in	284			
Cascading flow in	280F	281	283F	286F
Circulating pool in	280	280F	283F	286F
Discussed	278			
Flow behavior in	280	280F	283F	286F
Hydrocyst formation in	282	282F	284F	
Ideal fluid for	286			
Localized pooling in	285			
Polymers used in	278			
Process	279			

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Liquid rotational molding *(Continued)*				
Process controls for	285			
Rimming flow in	280F	281	283F	286F
Role of reaction in	285			
Role of gelation in	285			
Solid body rotation in	281	283F	286F	
Time-dependent viscosity in	279	279F		
LLDPE				
See also Polyethylene, linear low-density				
Crystallinity of	20T			
M				
Machines				
Basic elements of	112			
Clamshell	115	115F		
Cooling design in, *see Cooling*				
Compared with competition	111			
Electrically-heated molds for	120	120F	121F	
Fixed-arm carousel	117	118F		
Limiting factors	118			
Heat transfer in, *see Heat transfer*				
Home-built	111			
Independent-arm carousel	118	119F		
Advantages of	118			
Infrared heated	121			
Make-Vs-buy	111			
Oil-jacketed molds for	119			
Oven design in, *see Oven*				
Process control of, *see Process control*				
Rock-and-roll	113			

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
Machines *(Continued)*			
Shuttle	116	117F	
Types of, discussed	112		
Vertical	116	116F	
MDPE, *see* Polyethylene, medium-density			
Mechanical Properties	16		
Mechanical test			
Creep, defined	54		
Creep modulus	55		
Creep rupture	55		
Defined	54		
Flexural fatigue	55		
Flexural modulus	54		
Tensile modulus	54		
MEKP, *see* Methyl ethyl ketone peroxide			
Melt flow index	28		
See also Melt index			
Described	44		
Melt index	28	45F	64
HDPE	24		
LDPE	22		
MDPE	23		
Polyethylene property changes with	25T		
Process effects on	352F		
Quality control of	43	44	
Described	44		
Melt index test conditions			
Nonpolyolefins	44	45T	
Polyolefins	45T	46T	
Melt indexer	44	45F	

This page has been reformatted by Knovel to provide easier navigation.

Index terms		Links
Melt viscosity	15	43
Melt elastic modulus	64	
Melting temperature, defined	20	
Methyl ethyl ketone peroxide, catalyst for Unsaturated polyester resin	42	
Micropellet	46	
See also Polyvinyl chloride		
Coloring of	95	
Comparison with conventional pellet	94	95T
Discussed	93	
Method of production	93	
Processing comparison with powder	94	95T
Polyethylene	69	
PVC, discussed	96	96T
Reason for use	93	
Mold charging, schematic	5	2F
Mold cooling, schematic	5	2F
Mold heating, schematic	5	2F
Mold release	103	
Cost of	199	
Discussed	196	
Disiloxanes	197	
Early part release with	199	
Fluoropolymers	197	
Selection criteria for	198	
Silicone	197	
Spray-on	197	
Surfaces coated by	198	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Molds				
Air flow around deep pockets	136	136F		
Air flow using baffles	136	136F		
Air flow using venturi	136	137F		
Alignment methods for	165	164F		
Aluminum	150	150F	150T	152
Cast	150	152	154F	
Welded	152			
Machined	152	152F		
Clamping of	166	166F		
Commercial	149			
Design of				
Discussion	160			
For pressurization	276			
Parting line	161			
Butt or flat	161	161F		
Lap joint	162	162F		
Tongue-and-groove	162	163F		
Gaskets	163	163F		
Electroformed nickel	149	150T	154	155F
Frames for	165			
Heat transfer to	213			
J-clamps for	166	168F		
Manual clamps for	166			
Materials for				
Discussed	149			
Properties	150T			
Nonmetallic	149			
Pressure buildup without venting	183			
Pressurization for	340			

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Molds *(Continued)*				
Pressurized	146			
Pry points, location for	167	167F		
Sheet-metal	149	149F	150T	151
Spiders for	165	165F		
Surfaces coated with mold releases	198			
Surface finishes for	196			
Thermal behavior of				
Various types	156	157F	158F	159F
Equivalent mechanical thickness	156	157F		
Equivalent static thermal thickness	157	158F		
Equivalent transient thermal thickness	159	159F		
Toggle clamps for	166	167F		
Use of drop-box in	297			
Use of drop-box on	296	297F		
Venting of, *see Venting*				
Moment of area, second, *see Moment of inertia*				
Moment of inertia, defined	315			
Morphology				
Changes in PP, due to cooling rate	270T	273	273T	
Crystallinity level and	267	267T		
Effects of additives on	272	272T		
Recrystallization rates and	267	268T	269F	270T

N

Natural gas combustion	129	130T		
Nylon	9			
As thermoplastic	19			
Chemical structure	31			
Chemical types	32T			

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links	
Nylon *(Continued)*		
Crystallinity of	20T	32
Fiber-reinforced	9	
Melting temperature	32T	
Moisture concerns with	310	
Rotational molding grades	32	32T
Nylon 6, WLF constants for	324T	
Nylon 12, as liquid polymer	40	
O		
Odor		
Defined	62	
Test		
Olfactory	62	
Gas chromatography	62	
Oven time	14	
Effect on design parameters	351T	
Oven temperature	14	
Oven		
Air flow around molds with deep pockets	136	136F
Air flow in	136	
Design of, discussed	127	129
Efficiency of operation of	130	
Heat transfer in	131	
Heat transfer in		
Examples of	133	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
P			
PA-6			
See also Nylon: Polycaprolactam			
As liquid polymer	36		
Flexural modulus	32		
Heat deflection temperature	32		
Melting temperature	32		
Part design			
Acute-angled corners in	346	347F	
Aesthetics	307		
Almost kiss-offs in	312		
Appearance effect on	308		
Application effect on	308		
Assembly constraints effect on	309		
Bridging criteria for	311		
Cavity depth criteria for	312		
Competition effect on	309		
Computer-aided technique effect on	310		
Concerns of warpage in	311		
Control of wall thickness in	312		
Coordinate measuring machine use in	360		
Corner radius guidelines in	345	345T	347F
Cost effect on	309		
Criteria	307		
Criteria for kiss-off	318		
Cycle time effect on	310		
Decoration effect on	309		
Detents in	312		
Dimensional tolerance effect on	31		
Draft angles	341	342T	

This page has been reformatted by Knovel to provide easier navigation.

Index terms		Links
Part design *(Continued)*		
Female molds in	312	
Polymer-specific	341	342T
Texture	342	342T
Environment effect on	308	
External threads in	312	349
Fiber-reinforcement in	312	
Flat panels in	311	
General guidelines for, discussed	310	
General considerations for	335	
Gussets in	312	
Holes in	349	
Improving mechanical strength through	312	
Insert	349	
Criteria for	312	
Stresses around	312	
Internal threads in	312	349
Kiss-offs in	312	
Limitations of	309	
Market considerations	307	
Material choice effect on	309	
Mechanical		
Criteria for	314	
Discussion	307	317
Metal molded-in inserts for	313	
Minimum wall thickness in	336	
Mold cost effect on	309	
Molded-in holes in	312	
Mold texture transfer to parts in	312	
Nominal wall thickness in	336	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Part design *(Continued)*				
Parallel walls in	311	348		
Part function effect on	308			
Part wall separation for	348			
Philosophy	307			
Powder flow effect on	310			
Pressurization effects on	340			
Process effects on				
Discussion	350			
Impact	350	350F		
Melt index	352F			
Radius concerns in	312	313		
Right-angled corners in	345			
Ribs in	311			
Rim stiffening in	312			
Shrinkage guidelines in	337			
Size effect on	309			
Surface decoration; *see Decoration*				
Wall thickness considerations for	311			
Wall thickness in	336	337T		
Wall thickness limitation effect on	309			
Wall thickness range in	337T			
Warpage guidelines for	344	344T		
Warpage in	311			
Undercuts in	311	312		
Particle size distribution	75			
Data presentation	79	79F	80T	80F
Discussed	74			
Dry sieving	77			
Elutriation	78			

This page has been reformatted by Knovel to provide easier navigation.

Index terms		Links
Particle size distribution *(Continued)*		
Fluidization	79	
Light scattering	78	79
Measurement	77	
Sedimentation	78	
Streaming	78	
Test method	76	78
Factors affecting	78	
Test purpose	77	
Particle shape		
Acicular	81	
Discussed	81	
Effect on part performance	81	
Methods of classification	81	
Particle size analyzers	82	
Physical methods	82	
Shape factor	81	82T
Spherical	81	
Squared-egg	81	
Terms defined	82T	
Particle size analysis	77	
Parting line		
See also Molds, design of, parting line		
Butt or flat	161	161F
Design of	161	
Gaskets	163	163F
Lap joint	162	162F
Tongue-and-groove	162	163F
See also Part design		

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links
Parts	
Blowhole problems in 183	
Cutout areas in 172	
Failure	
Discussed 307	
Fracture 307	
Creep 307	
Crazing 307	
Stress cracking 307	
Fatigue 307	
Adhesive failure 308	
Warpage 308	
Shrinkage 308	
Color change 308	
Additive migration 308	
Cracking element migration 308	
Inserts for 168	
Kiss-offs for 172	173F
Mechanical fastening of 169	
Molded-in handles for 173	
Molded-in inserts for 169	170F
Molded-in threads for 171	171F
Post-molded fasteners for 169	
Self-tapping screws for 168	
Suck-hole problems in 185	
Temporary inserts for 173	
Warpage with mold release 199	
PC, *see* Polycarbonate	
PEEK 9	
See also Polyether-ether ketone	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links
Phenolic	9
As thermoset	19
Crosslinked, discussion	19
Pigments	
Classes of	101
Classification of	104T
Color shift in	103
Discussion of	101
Dry-color blending of	101
Heavy metals, restricted use of	101
Organics	102
Azo-type	102
Polycyclic-type	102
Processing concerns of	102
Fluorescents	103
Plate-out of	103
Special-effect	103
Temperature effect on selection of	101
Pinholes	15
Plaster, molding, properties	154
PMMA, *see* Polymethyl methacrylate	
Poly-a-aminoacid, *see Nylon*	
Polyacetal	9
See also POM, Polyoxymethylene	
Polyamide, *see Nylon*	
Polybutylene	9
Polycaprolactam	
Chemical structure	39
Defined	32
Fillers for	41

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
Polycaprolactam *(Continued)*			
Gellation rate	40		
General production method	40		
Time-dependent crystallinity	40F		
Time-dependent viscosity during reaction	39F		
Polycarbonate	9		
As thermoplastic	19		
Chemical resistance, discussed	34		
Chemical structure	33		
Drying for rotational molding, discussed	33	34T	
Flexural modulus	33		
Heat distortion temperature	33		
Impact strength, discussed	33		
Moisture concerns with	310		
WLF constants for	324T		
Polyester			
Unsaturated	9		
As thermoset	19		
Polyether-ether ketone	21		
As thermoplastic	19		
Polyethylene terephthalate, crystallinity of	20	20T	
Polyethylene			
As thermoplastic	19		
Branched, *see* Polyethylene, low-density			
Chemical structure	22		
Crosslinked	9		
Advantages	58		
Crosslinking agents	27	58	59T
Density	27		
Discussion	19	27	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links
Polyethylene *(Continued)*	
Environmental stress crack resistance	27
Flexural modulus	27
Gel content	27
Peroxide level	60F
Time dependency	60F
Test	59
Level, procedure	59
Shore hardness	27
Crystallinity of	20T
Early applications	6
High-density	
Chain configuration	23F
Crystalline morphology	24
Crystallinity	24
Defined	24
Density	24
Environmental stress crack resistance	24
Flexural modulus	24
Melt index	24
High-pressure, *see* Polyethylene,low-density	
Low-density	
Chain configuration	23F
Crystallinity	22
Defined	22
Density	22
Environmental stress crack resistance	22
Flexural modulus	22
Melt index	22
Shore hardness	22

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links
Polyethylene *(Continued)*	
Low-pressure, *see* Polyethylene, high-density	
Linear, *see* Polyethylene, high-density	
Linear low-density	
Chain configuration	23F
Crystallinity	27
Density	26
Defined	25
Environmental stress crack resistance	27
Flexural modulus	27
Medium-density	
Crystallinity	23
Defined	23
Density	23
Environmental stress crack resistance	23
Flexural modulus	23
Melt index	23
Metallocene, discussed	26
Micropellet	69
Odor	15
Powder	69
WLF constants for	324T
Polyimide	21
Polymer morphology, discussed	20
Polymethyl methacrylate, chemical structure	35
Polyolefin	7
Polypropylene	9
As thermoplastic	19
Atactic, defined	28
Chemical structure	28

This page has been reformatted by Knovel to provide easier navigation.

Index terms		Links
Polypropylene *(Continued)*		
Copolymer		
Defined	29	
Effect on properties	29	29T
Crystallinity of	20	20T
Fillers in	29	
High-temperature stability of	29	
Homopolymer, flexural modulus	28	
Isotactic, defined	28	
Melt flow index	28	
Recrystallization of	30	
Syndiotactic, defined	28	
WLF constants for	324T	
Polystyrene	9	
See also Styrenics		
As thermoplastic	19	
Discussed	35	
Impact, discussed	35	
WLF constants for	324T	
Polytetrafluoroethylene, crystallinity of	20	
Polyurethane	9	
As liquid polymer	37	
As thermoset	19	
Chemical structure	41	
Nature of reaction	42	
Time-dependent viscosity during reaction	41	
Polyvinyl chloride	21	
As thermoplastic	19	
Chemical structure	30	
Drysol, discussed	30	

This page has been reformatted by Knovel to provide easier navigation.

Index terms		Links
Polyvinyl chloride *(Continued)*		
Drysol hardness	31	
Drysol v. micropellet	96	96T
Liquid	6	
Micropellet	31	
Micropellet characteristics	96	96T
Plastisols, discussed	30	
Plastisol hardness	30	
Plastisol v. micropellet	96	96T
Role of plasticizers in	30	
Types of additives for	30	
Porosity, discussed	242	
Powder density		
Discussed	84	
Related to powder flow	85F	
Powder		
Coalescence	12	
Consolidation	14	
Densification	12	
Fusion	14	
Sintering	15	
Size	21	
Powder particle characterization, quality control	44	
Powder flow		
Discussed	74	83
Effect of tails on	83	
Grinding factors affecting	89	
Related to powder density	85F	
Test method	84	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Powder packing	85			
See also Powder flow; Particle shape				
Bulk density				
Fluidized	88T			
Measurement	84F	88		
Poured	88	88T		
Tamped	88	88T		
Vibrated	88	88T		
Deviation from ideal packing	86			
Equal spheres	85	86F	86T	
Packing fraction defined	85			
Particle size distribution effect	87			
Powder quality				
See also Grinding				
Discussed	88			
Grinding factors effecting	89			
Powder				
Airborne dust generation with	207			
Antistatic agents for	105			
Avalanche flow of	208	208F	209T	222
Bed behavior during heating	222			
Bubble dissolution in coalesced	235F			
Bulk density of various	206T			
Carbon black in	106			
Coalescence	203	235F		
Defined	223			
Coulomb flowing	207			
Temperature effect on	219			
Densification in	203	235F		
Air absorption	238			

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
Powder *(Continued)*			
Rayleigh.s model for	238		
Capillary action	236		
Defined	236		
Network collapse	236	237F	238F
Particle size distribution during coalescence	242		
Rate of	242		
Three mechanisms for	234		
Under vacuum	237		
Flow aspects of	206		
Fluidizing	207		
Mathematical modeling			
Bed	248		
Static bed	249		
Circulating bed	248	250	
Moisture concerns with	310		
Neck growth			
Compared with heating profile	226F		
Defined	223		
Viscous model	225	225F	227F
Neck growth rate	226	227T	
Creep compliance model	232	232F	233F
Hertzian	228		
Linear viscoelastic	229F	230	231F
Newtonian	227F	228	
Packing aspects of	205		
Polyethylene	69		
Polymer elasticity effect on coalescence of	234		
Rheology of flowing	210		
Rotating cylinder flow of	211	212F	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links			
Powder *(Continued)*				
Sintering of, defined	223			
Slip flow of	208	208F	209T	222
Steady-state circulation of	207	208F	209T	222
Stearates for	106			
UV additives for	106			
Viscous flowing	207			
Process control				
Discussed	138			
Inner cavity air temperature monitoring for	140			
Process cycle				
Discussion of	201			
Steps in	201	204	205T	
Processing and properties, general considerations	14			
Propane combustion	129	130T		
PS, *see* Polystyrene; Styrenics				
PSD	74	77		
See also Particle size distribution				
Pulverization, described	69			
P-V-T curves				
HDPE	338F			
Polycarbonate	339F			
Shrinkage and	337			
PVC plastisol	9	21		
As liquid polymer	36			
Effect of heat on molecular characteristics	37F			
Effect of heat on viscosity	38F			
Fusion	37F	38		
Gellation	37F	38		
Method of production	38			

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
PVC plastisol *(Continued)*			
Product types	39		
Shore hardness	39		
PVC, *see* Polyvinyl chloride			
Q			
Quality assurance, discussion	360		
R			
Rayleigh.s equation			
Inviscid	238		
Newtonian	238		
Viscoelastic	239		
Recrystallization, part design restrictions for	311		
Ribs, design criteria for, discussed	311		
Rock-and-roll machine	113	114F	115
Oven design	114F	115	
Products made on	113		
Rotation			
Fixed ratio, discussed	125		
Major-to-minor axis ratio	125		
Speed of, discussed	125		
Speed ratio			
Defined	126		
Recommended for various geometries	126T		
Rotational molding			
Advantages	10	12	14
Applications	3T		
Basic process	5	10	
Cooling	16		

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
Rotational molding *(Continued)*			
Competition	4	6	10T
Defined	4		
Degradation	15		
Design	8	11	
Desirable polymer characteristics	64		
Disadvantages	10	14	
Heating	15		
History	6		
Internal surface appearance	15		
Markets	4	5F	
Materials	9	10F	
Molder consumption	21T		
Nature of polymer in	69		
Polymer use	21T		
Powder flow	15		
Rotational molding process			
Limitations	145		
Advances in	146		
Rotocasting, *see* Rotational molding			
Rotomolding, *see* Rotational molding			

S

SAN, *see* Styrene-acrylonitrile			
Service station, discussed	144		
Shrinkage			
Discussion	337		
Guidelines for	340		
Linear	338	340T	
Volumetric, discussion	338		

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links
Shuttle machine	116 117F
Dual carriage	117 117F
Sieve technology	
Bulk density	46
Described	46
Dry sieving	46
Pourability	46
ARM recommendation	46
Sieve	
See also Powder technology	
Grinding	71
Dry, types of	77
Elutriation	78
Screen sizes, discussed	46
Shaker sizes	76F
Sizes of	75T
Sonic sifter	78
Silicone	9
As liquid polymer	37
Chemical structure	43
Method of reaction	43
Sintering	26
See also Coalescence	
Slip casting, ceramics	7
Slush molding	278
Society of Plastics Engineers Rotational Molding Division	12
Spin casting	7
Stress concentration factor	346F
Stress-cracking	57

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
Styrene-acrylonitrile, *see Styrenics*			
Styrenics, chemical structure	35		
Surface treatment			
Activation methods for	104		
Applied graphics as	105	105F	
Discussed	104		
Plasma	104		
T			
Tack temperature			
Amorphous	219	220T	
Crystalline	219	220T	
Defined	219		
Related to kink temperature	220	253	253T
Temperature measurement			
Correlation of			
Bubble dissolution time	142	142F	
Coalescence time	141		
Part release from mold	143		
Process step	140	141F	
Recrystallization time	143		
Infrared method	144		
Inner cavity air temperature	140		
Interpretation	140	141F	
Mold assembly	139		
See also Heat transfer			
Tensile modulus, *see* Mechanical test, tensile, modulus			
Testing protocol			
Actual part	47		
Costs	48	49T	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links
Testing protocol *(Continued)*	
Defined	47
Full-scale	47
Segment	48
Test acceptability criteria	48
Testing	
Environmental stress crack resistance	50 50F
Full-scale	49
Molded density	51
Sections	50
T_g, *see* Glass transition temperature	
Thermal lag	214 222 245
See also Heat transfer, to mold	
Mathematical model of	245
Thermal conductivity, of powder	217 218F
Thermal diffusivity	248
Powder	218
Thermoplastics	
Defined	19
Discussed	6
Thermosets	
See also Thermosetting polymers	
Defined	19
Rotational molding advantages	43
Thermosetting polymers, liquids	36
Thermosetting liquids, nature of reaction	36
Thermosetting, discussed	6
Titanium dioxide	
As opacifier	107
As UV additive	107

This page has been reformatted by Knovel to provide easier navigation.

Index terms		Links
Tm, *see* Melting temperature		
Trimming		
Cutting characteristics	356T	
Various polymers	356	
Discussion	354	
Multiaxis	354	356T
Troubleshooting		
Discussion	360	
Guidelines, Appendix A		
U		
UHMWPE, *see* Ultrahigh molecular weight, polyethylene		
ULE-84 tunnel test	62	
See also Fire retardancy		
UL 94	63	
See also Fire retardancy, standard match test		
Ultrahigh molecular weight polyethylene, characteristics	22	
Undercuts, design criteria for, discussed	311	
Unload/load process station, *see* Service station		
Unsaturated polyester resin		
As liquid polymer	37	
Chemical structure	42	
Fillers for	42	
Processing difficulties with	42	
Reaction via MEKP	42	
UPE, *see* Unsaturated polyester resin		
UV additive		
Carbon black as	106	
Classification of	106	
Hindered amine light stabilizers as	106	

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links		
UV additive *(Continued)*			
Titanium dioxide as	107		
V			
Venting			
Design guidelines for	186	190F	192F
Discussion	183		
Disposable	193		
Permanent	193	194F	
Pressure buildup without	183		
Requirements for	195		
Types of	193		
Selection criteria	193		
Vacuum without	185		
Venturi			
See also Molds			
Mold design with	136	137F	
Vertical machine, discussed	116	116F	
W			
Wall thickness			
Calculation of	174		
Maximum allowable	180	181F	
Warpage	16		
Weathering			
Accelerated tests	61		
Acid rain	61		
Defined	61		
Resistance of polymers	61		
Ultraviolet effect	61		

This page has been reformatted by Knovel to provide easier navigation.

Index terms	Links
Williams-Landel-Ferry model	323
Constants for	324T
WLF equation	323 324T
See also Williams-Landel-Ferry model	

X

XLPE, *see* Polyethylene, crosslinked

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